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ENGINEERING DATA ON NEW AEROSPACE STRUCTURAL MATERIALS

O. L. Deel, et al

Battelle Columbus Laboratories

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O. L. DEEL and H. MINDLIN

Battelle
Columbus Laboratories

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13. ABSTRACT

The major objectives of this research program were to evaluate newly developed materials of interest to the Air Force for potential weapons system usage, and then to provide "data sheet" type presentations of engineering data for these materials. The effort covered in this report has concentrated on 17-4 PH (H900) ESR bar, Udimet 710 forged bar, 7050-T7E56 hand forging, 2214-T351 plate, and Ti-6Al-4V (DBHT) diffusion bonded component.

The properties investigated include tension, compression, shear, bend, impact, fracture toughness, fatigue, creep and stress-rupture, and stress corrosion at selected temperatures.

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Corrosion Resistance						
Physical Properties						
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Nickel Base Alloy						
Aluminum Alloy						
Titanium Alloy						
17-4 PH ESR						
Udimet 710						
7050-T7E56						
2214-T351						
Ti-6Al-4V						

Security Classification

ENGINEERING DATA ON NEW
AEROSPACE STRUCTURAL MATERIALS

O. L. Deel and H. Mindlin

IC

FOREWORD

This report was prepared by Battelle's Columbus Laboratories, Columbus, Ohio, under Contract F33615-71-C-1262. This contract was performed under Project No. 7381, "Materials Applications", Task No. 738106, "Engineering and Design Data". The work was administered under the direction of the Air Force Materials Laboratory, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio, by Mr. Clayton Harmsworth (AFML/LAE), technical manager.

This final report covers work conducted from April, 1971, to July, 1972. This report was submitted by the authors on August 9, 1972.

This technical report has been reviewed and is approved.

A. Olevitch
A. Olevitch
Chief, Materials Engineering Branch
Materials Support Division
Air Force Materials Laboratory

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INTRODUCTION

The selection of materials to most effectively satisfy new environmental requirements and increased design load requirements for advanced Air Force weapons systems is of vital importance. A major difficulty that design engineers encounter, particularly for newly developed materials, materials processing, and product forms, is a lack of sufficient engineering data information to effectively evaluate the relative potential of these developments for a particular application.

In recognition of this need, the Air Force has sponsored several programs at Battelle's Columbus Laboratories to provide comparative engineering data for newly developed materials. The materials included in these evaluation programs were carefully selected to insure that they were either available or could become quickly available on request and that they would represent potentially attractive alloy projections for weapons system usage. The results of these programs have been published in four technical reports, AFML-TR-67-418, AFML-TR-68-211, AFML-TR-70-252, and AFML-TR-71-249.

This technical report is a result of the continuing effort to relieve the above situation and to stimulate interest in the use of newly developed alloys, or new processing techniques for older alloys, for advanced structures or propulsion systems.

The materials evaluated under this program are as follows:

(1) 17-4-PH (H900) ESR Bar

(2) Udimet 710 Forged Bar

(3) 7050-T7E56 Hand Forging

(4) 2214-T351 (Alcoa 417 Process) Plate

(5) Ti-6Al-4V (DBHT) Diffusion Bonded Component.

The temper or heat-treat conditions selected for evaluation are described in each alloy section.

The program approach was, as on previous contracts, to search the published literature and to contact metal producers and aerospace companies for any pertinent data. If very little pertinent information was available, a complete material evaluation was conducted. Upon completion of each material evaluation, a "data sheet" was issued to make the data immediately available to potential users rather than defer publication to the end of the contract term and the summary technical report. These data sheets are reproduced in Appendix III of this report.

Detailed information concerning the properties of interest, test techniques, and specimen types are contained in Appendices I and II of this report.

17-4 PH (H900) Bar (ESR)

Material Description

This alloy is one of the family of precipitation hardening stainless steels which have found wide usage in aerospace, industrial, and commercial applications. The particular material used in this evaluation was produced by the Electroslag Remelting (ESR) process. In this process an electrode (in this case, air melted 17-4 PH) is melted in a resistance heated molten bath of flux contained in an open-bottomed water-cooled metal mold. The melted metal forms a pool beneath the flux bath and progressively solidifies forming an ingot which is continuously extracted from the mold.

The metal is refined and desulfurized by flux action and the microstructure is improved by controlled solidification.

The material used in this evaluation was a 3.3-inch-diameter bar from Heat 02298. Chemistry was as follows:

Chemical Composition	Percent
Carbon	0.04
Manganese	0.70
Silicon	0.41
Phosphorus	0.15
Sulfur	0.08
Chromium	15.9
Nickel	4.45
Copper	3.45
Columbium	0.23
Iron	Balance

Processing and Heat Treating

All specimens were machined from the longitudinal direction, except for both longitudinal and transverse Charpy impact specimens, as shown in Figure 1. They were then heat treated at 900 F for 1 hour to Condition H900.

Test Results

Tension. Results of longitudinal tests at room temperature, 400 F, 700 F, and 900 F are given in Table 1. Stress-strain curves at temperature are shown in Figure 2. Effect of temperature curves are presented in Figure 4.

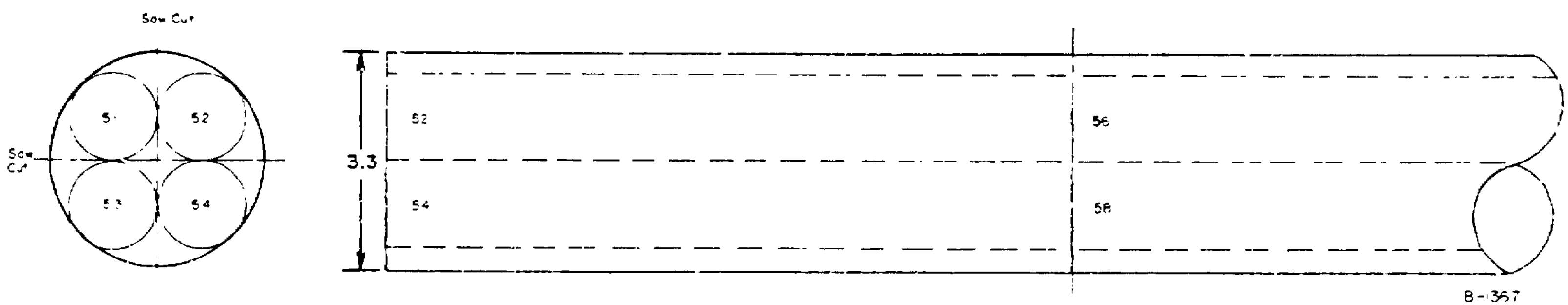

FIGURE 1. SPECIMEN LAYOUT FOR 17-4 PH (H900) BAR (ESR)

Compression. Results of longitudinal tests at room temperature, 400 F, 700 F, and 900 F are given in Table II. Stress-strain and tangent-modulus curves are presented in Figure 3. Effect of temperature curves are shown in Figure 5.

Shear. Results of room temperature pin shear tests are given in Table III.

Impact. Charpy test results for longitudinal and transverse specimens at room temperature are given in Table IV.

Fracture Toughness. Slow-bend tests were conducted at room temperature. Results are given in Table V. The K_Q values obtained are considered valid K_{Ic} numbers by existing ASTM standards.

Fatigue. Axial load fatigue tests results for unnotched and notched longitudinal specimens are given in Tables VI and VII. S-N curves are presented in Figures 6 and 7 for room temperature, 400 F, and 700 F.

Creep and Stress-Rupture. Results of tests on longitudinal specimens at 700 F, 900 F, and 1100 F are given in Table VIII. Log-stress versus log-time curves are shown in Figure 8.

Stress Corrosion. Six specimens were tested as described in the experimental procedures section of this report. No cracks or failures occurred in the 1000 hour test duration.

Thermal Expansion. The coefficient of thermal expansion for this alloy is 6.5×10^{-6} in/in/F for 68 F to 900 F.

Density. The density of this material is 0.282 lb/in^3.

TABLE 1. TENSION TEST RESULTS FOR [illegible] (ESR)

Specimen Number	Ultimate Tensile Strength, ksi	0.2 percent Offset Yield Strength, ksi	Elongation in 2 inches, percent	Reduction in Area, percent	Tensile Modulus, 10^6 psi
		Room Temperature			
1L-1	201.4	189.6	16.2	50.0	28.5
1L-2	195.8	184.2	18.0	45.6	29.2
1L-3	194.4	182.9	17.2	48.2	28.3
		400 F			
1L-4	180.2	159.6	10.1	38.6	26.2
1L-5	176.4	160.2	11.6	38.0	26.3
1L-6	175.8	158.0	10.9	36.2	27.0
		700 F			
1L-7	160.0	142.6	9.9	38.6	24.0
1L-8	162.8	147.6	10.2	31.2	24.4
1L-9	158.3	144.8	9.7	34.9	23.6
		900 F			
1L-10	138.0	110.0	10.0	30.0	22.8
1L-11	142.2	108.0	9.5	38.0	20.9
1L-12	137.9	106.5	9.5	35.2	23.1

TABLE II. COMPRESSION TEST RESULTS FOR 17-4 PH (H900) BAR (ESR)

Specimen Number	0.2 Percent Offset Yield Strength, ksi	Compression Modulus, 10^6 psi
	Room Temperature	
2L-1	172.6	29.6
2L-2	170.0	30.1
2L-3	176.7	31.0
	400 F	
2L-4	147.6	27.0
2L-5	150.0	27.4
2L-6	146.2	26.2
	700 F	
2L-7	138.6	25.1
2L-8	138.6	24.0
2L-9	141.2	24.9
	900 F	
2L-10	117.0	24.2
2L-11	118.7	24.0
2L-12	117.0	23.4

TABLE III. SHEAR TEST RESULTS FOR 17-4 PH (H900) BAR (ESR)

Specimen Number	Ultimate Shear Strength, ksi
4L-1	117.0
4L-2	117.2
4L-3	117.0
4L-4	118.0

TABLE IV. IMPACT TEST RESULTS FOR 17-4 PH (H900) BAR (ESR)

Specimen Number	Energy, ft/lbs
Longitudinal	
10L-1	20.8
10L-2	21.0
10L-3	28.0
10L-4	16.4
10L-5	23.9
Transverse	
10T-1	19.0
10T-2	15.2
10T-3	21.9
10T-4	24.7
10T-5	17.6

TABLE V. FRACTURE TOUGHNESS TEST RESULTS
FOR 17-4 PH (H900) BAR (ESR)

Specimen Number	W, inches	a, inches	T, inches	P, lbs	Span, inches	$f(\frac{a}{W})$	K_Q
1	1.503	.568	.757	7,500	4.5	1.86	45.1
2	1.503	.553	.757	8,600	4.5	1.81	50.4
3	1.503	.570	.756	8,100	4.5	1.87	49.0

TABLE VI. AXIAL LOAD FATIGUE TEST RESULTS FOR UNNOTCHED 17-4 PH (H900) BAR (ESR)

Specimen Number	Maximum Stress, ksi	Lifetime, cycles
	Room Temperature	
5-2	150.0	23,300
5-3	145.0	27,100
5-1	140.0	69,900
5-4	135.0	33,900
5-5	130.0	117,300
5-6	125.0	109,500
5-7	120.0	7,458,300
5-9	110.0	338,700
5-10	105.0	11,419,500(a)
	400 F	
5-11	150.0	(b)
5-15	140.0	100
5-13	135.0	19,700
5-12	130.0	33,400
5-14	125.0	146,100
5-16	120.0	37,700(c)
5-17	120.0	1,327,100
5-28	100.0	5,137,100
5-29	90.0	10,026,000(a)
	700 F	
5-18	135.0	100
5-19	125.0	(b)
5-20	120.0	163,600
5-21	117.5	188,400
5-22	115.0	900
5-23	113.5	193,000
5-24	110.0	88,000
5-25	100.0	2,191,000
5-26	90.0	2,300,600
5-27	80.0	4,821,900
5-30	70.0	10,019,670(a)

(a) Did not fail.

(b) Failed on loading.

(c) Broke at thermocouple.

TABLE VII. AXIAL LOAD FATIGUE TEST RESULTS FOR NOTCHED (K_t = 3.0) 17-4 PH (H900) BAR (ESR)

Specimen Number	Maximum Stress, ksi	Lifetime, cycles
	Room Temperature	
5-1	130.0	1,400
5-2	120.0	2,400
5-3	90.0	6,100
5-4	70.0	7,800
5-6	60.0	18,500
5-5	50.0	41,700
5-7	40.0	60,300
5-8	30.0	14,853,100[a]
	400 F	
5-9	70.0	4,600
5-12	65.0	16,600
5-10	60.0	20,200
5-13	55.0	22,200
5-14	52.5	57,800
5-11	50.0	10,897,600[a]
	700 F	
5-15	70.0	1,900
5-16	65.0	4,000
5-17	60.0	7,300
5-18	55.0	19,600
5-19	50.0	61,100
5-20	45.0	11,386,900[a]

(a) Did not fail.

TABLE VIII. SUMMARY DATA ON CREEP AND RUPTURE PROPERTIES FOR 17-4 PH (H900) BAR (ESR)

Specimen No.	Stress, ksi	Temp, F	Hours to Indicated Creep Deformation, percent 0.1	0.2	0.5	1.0	2.0	Initial Strain, percent	Rupture Time, hr	Elongation in 2 in., percent	Reduction of Area, percent	Minimum Creep Rate, percent/hr
3-2	170	700	---	---	---	---	---	--	On Loading	11.1	56.6	--
3-5	160	700	0.1	1.4	45	800	3250(b)	1.341	625.8(a)	2.58	--	0.00041
3-10	140	700	10	120	2900(b)	---	---	0.778	599.0(a)	1.078	--	0.000087
3-1	100	900	0.35	0.7	3.7	11.4	22.5	0.489	34.8	14.1	51.9	0.062
3-2	80	900	1.0	4	18	75	130	0.426	184.8	22.2	50.5	0.0053
3-[illegible]	70	900	0.6	4.3	60	135	195	0.388	279.7	20.0	52.8	0.0050
3-9	50	900	45	250	500	---	---	0.133	641.7(a)	0.674	--	0.00041
3-4	40	1100	0.1	0.3	1.5	3.7	7.0	0.382	16.8	34.1	68.4	0.21
3-7	30	1100	0.5	2.0	10	25	45	0.297	95.1	39.3	79.4	0.025
3-8	20	1100	2.5	18	47	115	194	0.137	521.1	40.7	79.8	0.0051
3-11	[illegible]	1100	145	310	1550(b)	---	---	0	648.8(a)	0.290	--	0.00021

(a) Test discontinued.
(b) Estimate.

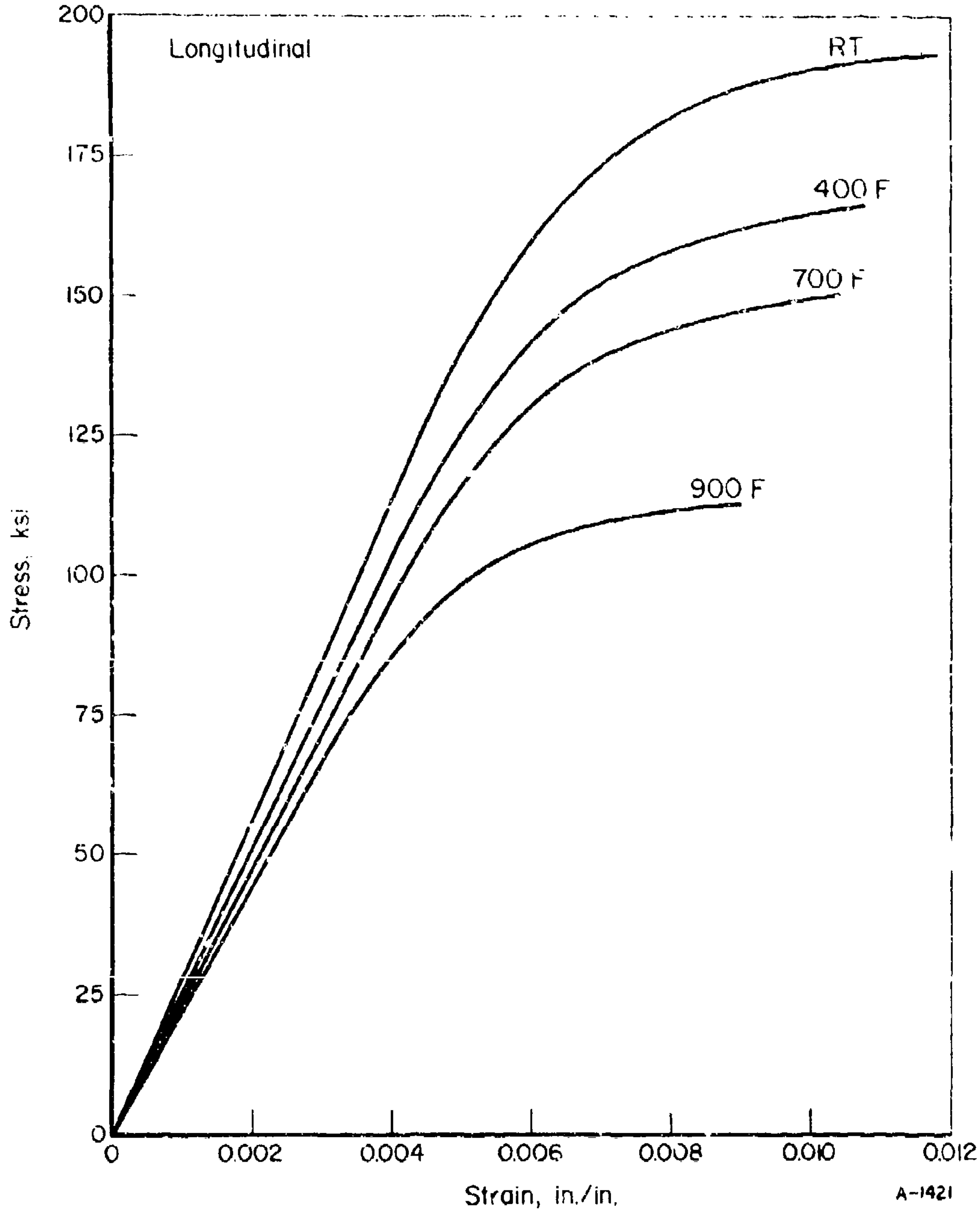

FIGURE 2. TYPICAL TENSILE STRESS-STRAIN CURVES FOR 17-4 PH (H900) BAR (ESR)

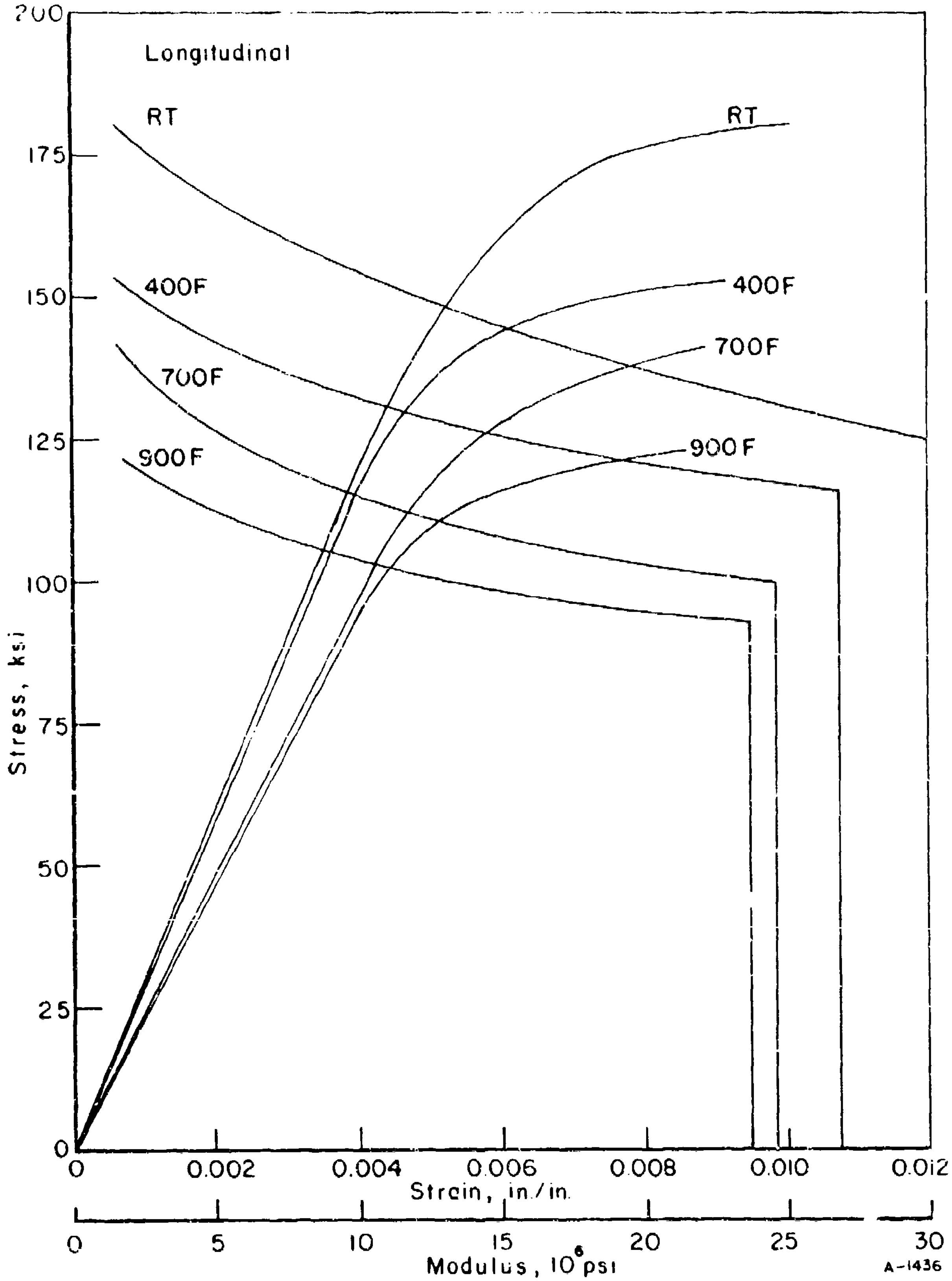

FIGURE 3. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES FOR 17-4 PH (H900) BAR (ESR)

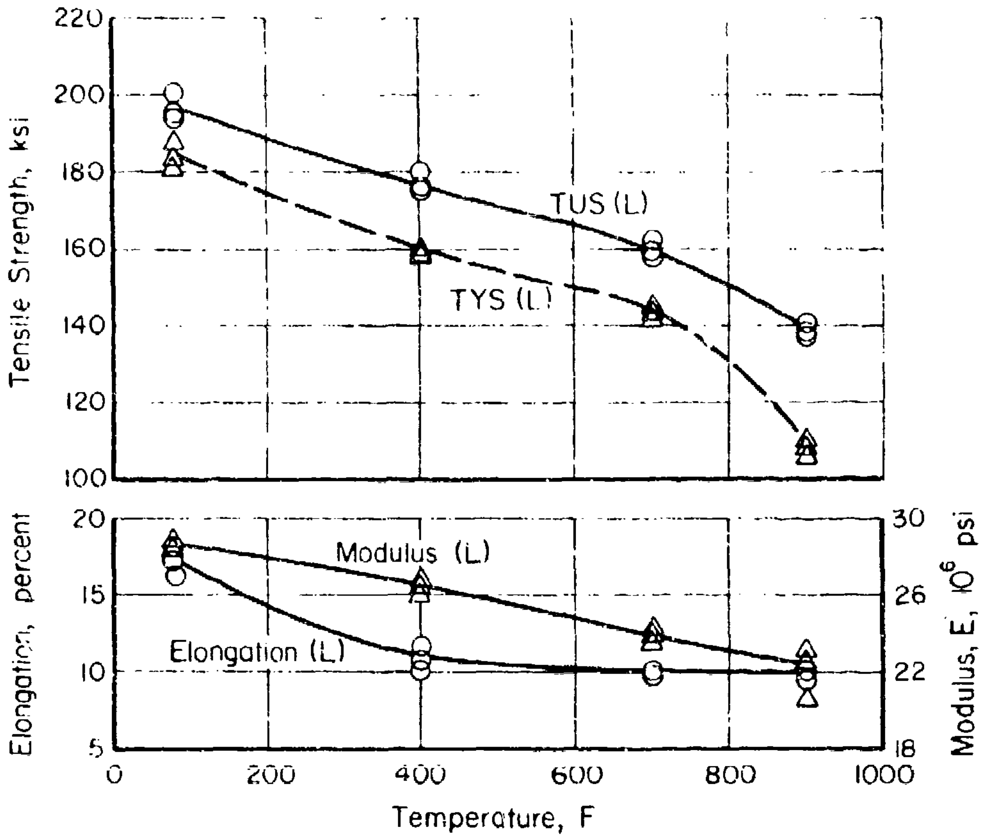

FIGURE 4. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF 17-4 PH (H900) BAR (ESR)

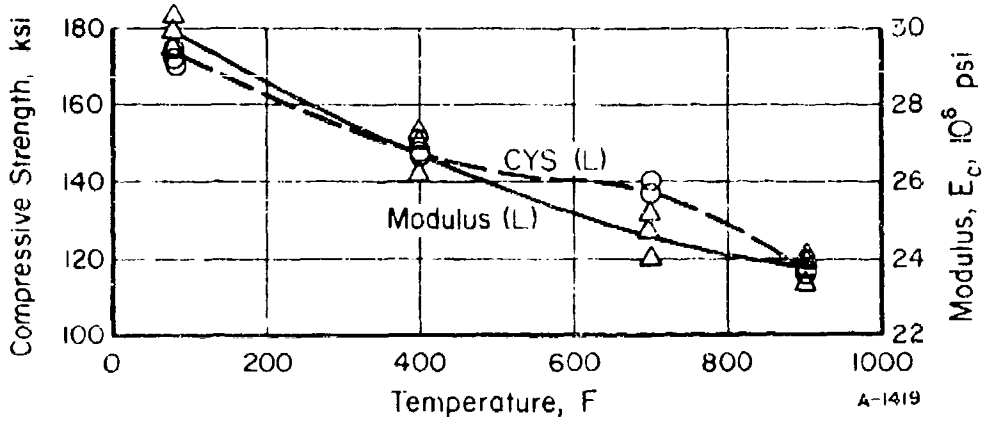

FIGURE 5. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF 17-4 PH (H900) BAR (ESR)

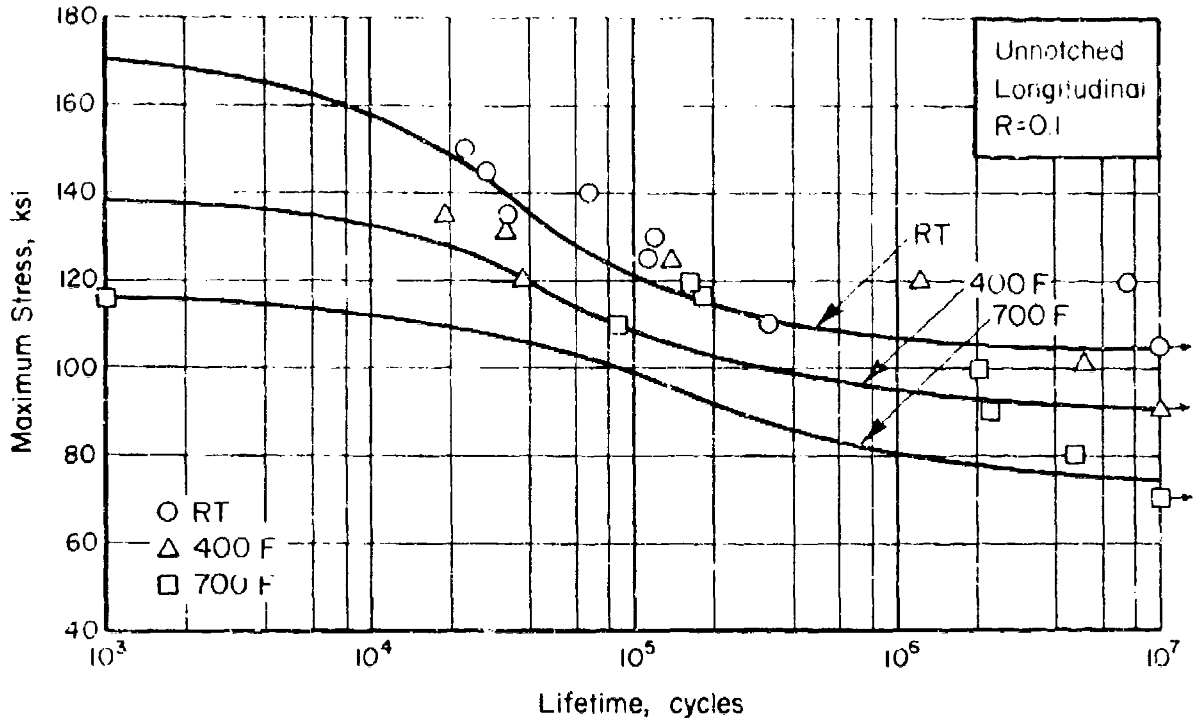

FIGURE 6. AXIAL LOAD FATIGUE RESULTS FOR UNNOTCHED 17-4 PH (H900) BAR (ESR)

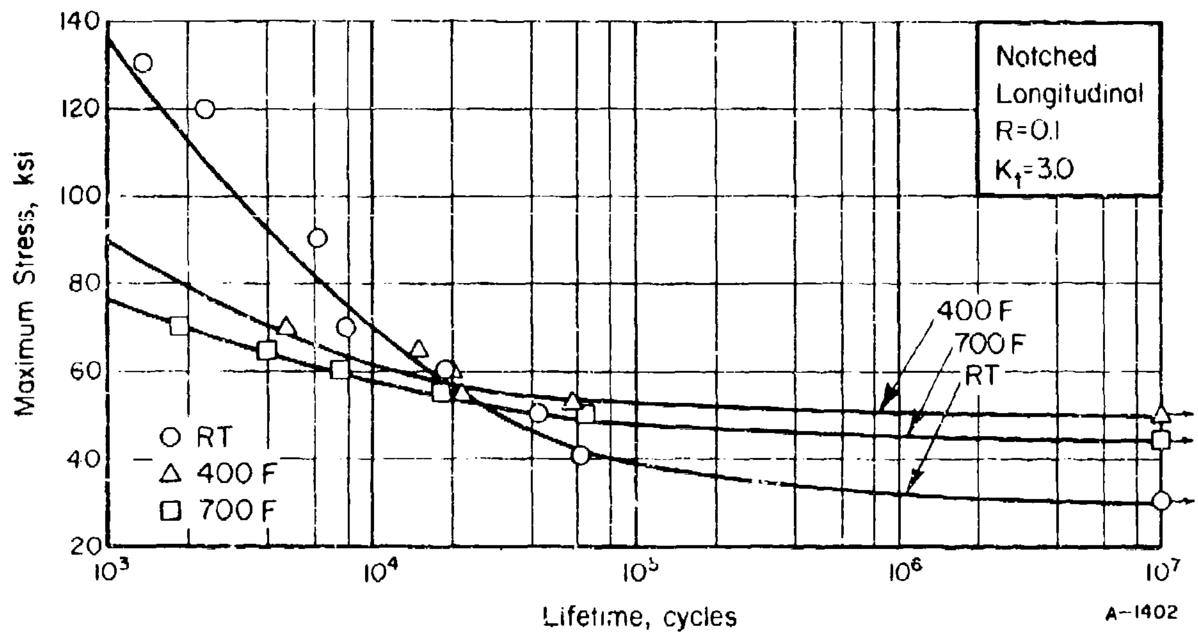

FIGURE 7. A[illegible] LOAD FATIGUE RESULTS FOR NOTCHED
([illegible].0) 17-4 PH (H900) BAR (ESR)

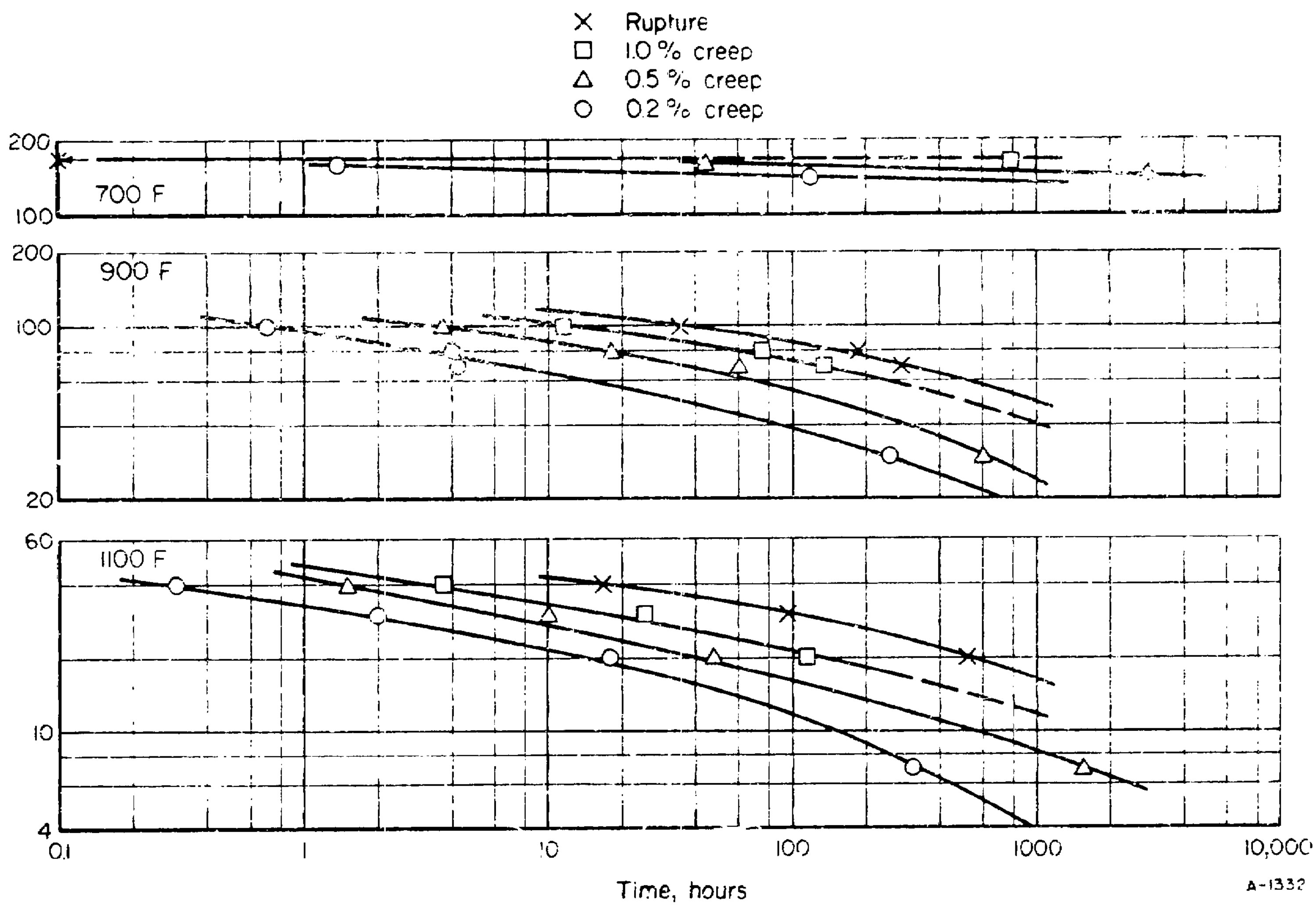

FIGURE 8. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR 17-4 PH (H900) BAR (ESR)

Udimet 710 Forged Bar

Material Description

Udimet 710 was recently developed by Special Metals Corporation to fill the need for a jet engine turbine blading alloy, combining the high strength and stability characteristics of Udimet 700 with the corrosion and sulfidation resistance of 18% chromium alloys such as the older Udimet 500 and Waspaloy. The alloy is designed for use in either the wrought or cast form. Data generated at Special Metals from laboratory heats show it to have rupture strengths superior to Udimet 700, good oxidation and hot corrosion resistance and excellent phase stability after extended exposure to stress and temperature. Data are now being generated from production scale heats for both cast and wrought forms.

The material used for this evaluation was Special Metal Corporation Heat No. 8-2814. The alloy was obtained as 1.875 inch diameter bar with the following composition:

Chemical Composition	Percent
Carbon	0.07
Manganese	0.10
Silicon	0.10
Chromium	18.0
Cobalt	14.8
Iron	0.14
Molybdenum	3.10
Tungsten	1.47
Titanium	4.88
Aluminum	2.51
Boron	0.018
Zirconium	0.04
Sulfur	0.003
Nickel	Balance

Processing and Heat Treating

Specimens were machined from the bar in the longitudinal direction as shown in Figure 9. Heat treating, as suggested by Special Metals, was as follows:

(1) 2150 F for 4 hours, air cool,

(2) 1975 F for 4 hours, air cool,

(3) 1550 F for 24 hours, air cool,

(4) 1400 F for 16 hours, air cool.

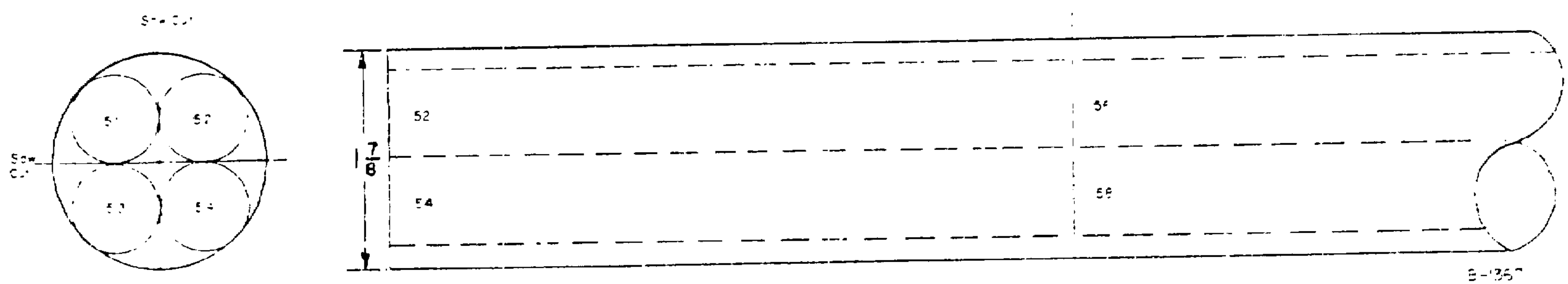

FIGURE 9. SPECIMEN LAYOUT FOR UDIMET 710 FORGED BAR

Test Results

Tension. Test results for longitudinal specimens at room temperature, 800 F, 1200 F, and 1800 F are given in Table IX. Stress-strain curves at temperature are shown in Figure 11. Effect of temperature curves are shown in Figure 12.

Compression. Test results for longitudinal specimens at room temperature, 800 F, 1200 F, and 1800 F are given in Table X. Stress-strain and tangent-modulus curves are shown in Figure 10. Effect of temperature curves are shown in Figure 13.

Shear. Test results are given in Table XI for longitudinal pin shear specimens.

Impact. Charpy test results for longitudinal specimens at room temperature are given in Table XII.

Fracture Toughness. Slow-bend fracture toughness tests were conducted at room temperature. Test results are given in Table XIII. Since the size ratio, $2.5 (K_Q/TYS)^2$, was greater than both the specimen thickness and crack length in all tests, the K_Q values are not considered valid K_{Ic} numbers by existing ASTM criteria.

Fatigue. Axial load fatigue test results for unnotched and notched longitudinal specimens at room temperature, 800 F, and 1200 F are given in Tables XIV and XV. S-N curves are presented in Figures 14 and 15.

Creep and Stress Rupture. Test results at 1000 F, 1400 F, and 1800 F are given in Table XVI. Log-stress versus log-time curves are presented in Figure 16.

Stress Corrosion. Tests were conducted as described in the experimental procedures section of this report. No failures or cracks occurred in the 1000-hour test duration.

Thermal Expansion. The coefficient of thermal expansion for this alloy is 8.7×10^{-6} in./in./F from 70 F to 1400 F.

Density. The density of this material is 0.292 lb/in.^{3}.

TABLE IX. TENSION TEST RESULTS FOR UDIMET 710 FORGED BAR

Specimen Number	Ultimate Tensile Strength, ksi	0.2 percent Offset Yield Strength, ksi	Elongation in 2 inches, percent	Reduction in Area, percent	Tensile Modulus, 10^6 psi
		Room Temperature			
1L-1	177.0	138.0	7.2	7.0	30.9
1L-2	178.0	139.0	7.7	9.6	27.9
1L-3	178.0	137.0	6.7	9.5	28.9
		800 F			
1L-4	167.8	123.2	7.6	9.6	24.3
1L-5	167.8	123.1	7.6	9.0	23.9
1L-6	162.6	122.2	7.6	9.0	24.4
		1200 F			
1L-7	183.0	118.5	16.0	13.6	21.4
1L-8	177.6	123.1	13.0	16.1	20.3
1L-9	191.0	127.1	17.0	14.0	20.9
		1800 F			
1L-10	53.4	38.2	29.8	32.0	18.6
1L-11	56.5	35.9	30.0	37.0	20.0
1L-12	55.0	36.9	30.2	37.0	17.9

TABLE X. COMPRESSION TEST RESULTS FOR UDIMET 710 FORGED BAR

Specimen Number	0.2 Percent Offset Yield Strength, ksi	Compression Modulus, 10^6 psi
	Room Temperature	
2L-1	150.0	30.9
2L-2	151.0	31.0
2L-3	148.0	30.0
	800 F	
2L-4	127.0	26.0
2L-5	127.0	25.0
2L-6	127.0	25.6
	1200 F	
2L-7	118.0	23.3
2L-8	119.0	22.1
2L-9	118.5	22.0
	1800 F	
2L-10	37.0	18.6
2L-11	38.0	18.0
2L-12	37.0	18.0

TABLE XI. SHEAR TEST RESULTS FOR UDIMET 710 FORGED BAR AT ROOM TEMPERATURE

Specimen Number	Ultimate Shear Strength, ksi
4L-1	123.1
4L-2	127.2
4L-3	125.1
4L-4	129.7

TABLE XII. IMPACT TEST RESULTS FOR UDIMET 710 FORGED BAR

Specimen Number	Energy ft lbs
10L-1	29.5
10L-2	26.0
10L-3	26.0
10L-4	25.0
10L-5	27.0
10L-6	33.0

TABLE XIII. FRACTURE TOUGHNESS TEST RESULTS FOR UDIMET 710 FORGED BAR

Specimen Number	W, inches	a, inches	T, inches	P, lbs	Span, inches	$f(\frac{a}{W})$	K_Q (a)
1	1.500	.750	.750	9,250	4.5	2.66	80.5
2	1.502	.765	.748	9,000	4.5	2.74	80.7
3	1.500	.749	.749	9,400	4.5	2.66	81.7
4	1.502	.762	.749	8,400	4.5	2.72	74.8

(a) Candidate fracture toughness values, K_Q, are invalid as K_{Ic} values since a, T, $< 2.5 \left(\frac{K_Q}{TYS}\right)^2$.

TABLE XIV. AXIAL LOAD FATIGUE TEST RESULTS FOR UNNOTCHED UDIMET 710 FORGED BAR

Specimen Number	Maximum Stress, ksi	Lifetime, cycles
	Room Temperature	
5-4	135.0	60,130
5-1	125.0	86,250
5-5	120.0	147,530
5-2	115.0	164,310
5-27	112.5	274,000
5-6	110.0	435,110
5-28	107.5	1,247,000
5-3	105.0	6,610,600
5-7	100.0	12,282,720(a)
	800 F	
5-17	110.0	17,000
5-16	100.0	107,900
5-13	95.0	125,200
5-19	90.0	82,300
5-20	85.0	173,200
5-21	80.0	197,300
5-22	75.0	838,600
5-23	70.0	977,700
5-24	65.0	739,500
5-25	55.0	6,488,000
5-26	45.0	16,419,400(a)
	1200 F	
5-9	120.0	100
5-10	100.0	86,100
5-11	95.0	119,300
5-12	90.0	284,700
5-13	85.0	122,200
5-14	80.0	1,626,200
5-29	77.5	10,489,900(a)
5-15	75.0	10,474,400(a)

(a) Did not fail.

TABLE XV. AXIAL LOAD FATIGUE TEST RESULTS FOR NOTCHED (K_t = 3.0) UDIMET 710 FORGED BAR

Specimen Number	Maximum Stress, ksi	Lifetime, cycles
	Room Temperature	
5-1	100.0	20,270
5-2	90.0	29,660
5-3	80.0	51,170
5-4	70.0	67,310
5-5	60.0	114,890
5-8	55.0	132,430
5-6	50.0	366,160
5-7	40.0	793,110
5-10	35.0	1,791,800
5-9	30.0	2,693,800
5-11	25.0	11,458,100[a]
	800 F	
5-18	65.0	13,700
5-19	60.0	20,600
5-20	55.0	21,500
5-21	50.0	73,800
5-22	45.0	134,800
5-23	40.0	6,707,000
5-24	35.0	680,100
5-25	30.0	10,013,600[a]
5-26	27.5	5,577,200
	1200 F	
5-17	65.0	5,200
5-12	60.0	7,600
5-15	55.0	9,800
5-13	50.0	42,100
5-16	45.0	62,900
5-27	42.5	10,321,900[a]
5-14	40.0	10,043,700[a]

(a) Did not fail.

TABLE XVI. SUMMARY DATA ON CREEP AND RUPTURE PROPERTIES FOR UDIMET 710 FORGED BAR

Specimen No.	Stress, ksi	Temp, F	Hours to Indicated Creep Deformation, percent					Initial Strain, percent	Rupture Time, hr	Elongation in 2 in., percent	Reduction of Area, percent	Minimum Creep Rate, percent/hr
			0.1	0.2	0.5	1.0	2.0					
3-4	181	1000	---	---	---	---	---	---	On Loading	25.3	27.6	---
3-6	175	1000	0.03	0.5	0.15	0.42	1.2	15.41	16.7	34.1	32.9	1.0
3-7	167	1000	0.05	0.08	0.30	1.5	5.0	9.367	100.3	26.7	27.4	0.15
3-8	150	1000	0.10	0.3	3.5	14.5	56	5.284	121.3[a]	8.360	---	0.015
3-10	120	1000	100	1500[b]	---	---	---	1.297	957.6[a]	1.478	---	0.00001
3-1	90	1400	0.02	0.03	0.04	0.15	0.45	0.719	2.9	20.7	34.9	2.7
3-2	70	1400	0.08	0.18	0.65	2.5	10	0.300	55.7	17.8	50.0	0.12
3-3	40	1400	20	90	420	1100	2450[b]	0.241	1095.7[a]	1.237	---	0.00074
3-5	20	1800	0.02	0.04	0.10	0.30	0.7	0.274	3.0	23.0	54.5	2.4
3-9	5	1800	3.0	7.5	20	45	77	---	266.7	24.5	51.7	0.011
3-11	2	1800	14	28	62	115	190	0.011	955.8	44.4	42.0	0.007

(a) Test discontinued.
(b) Estimate.

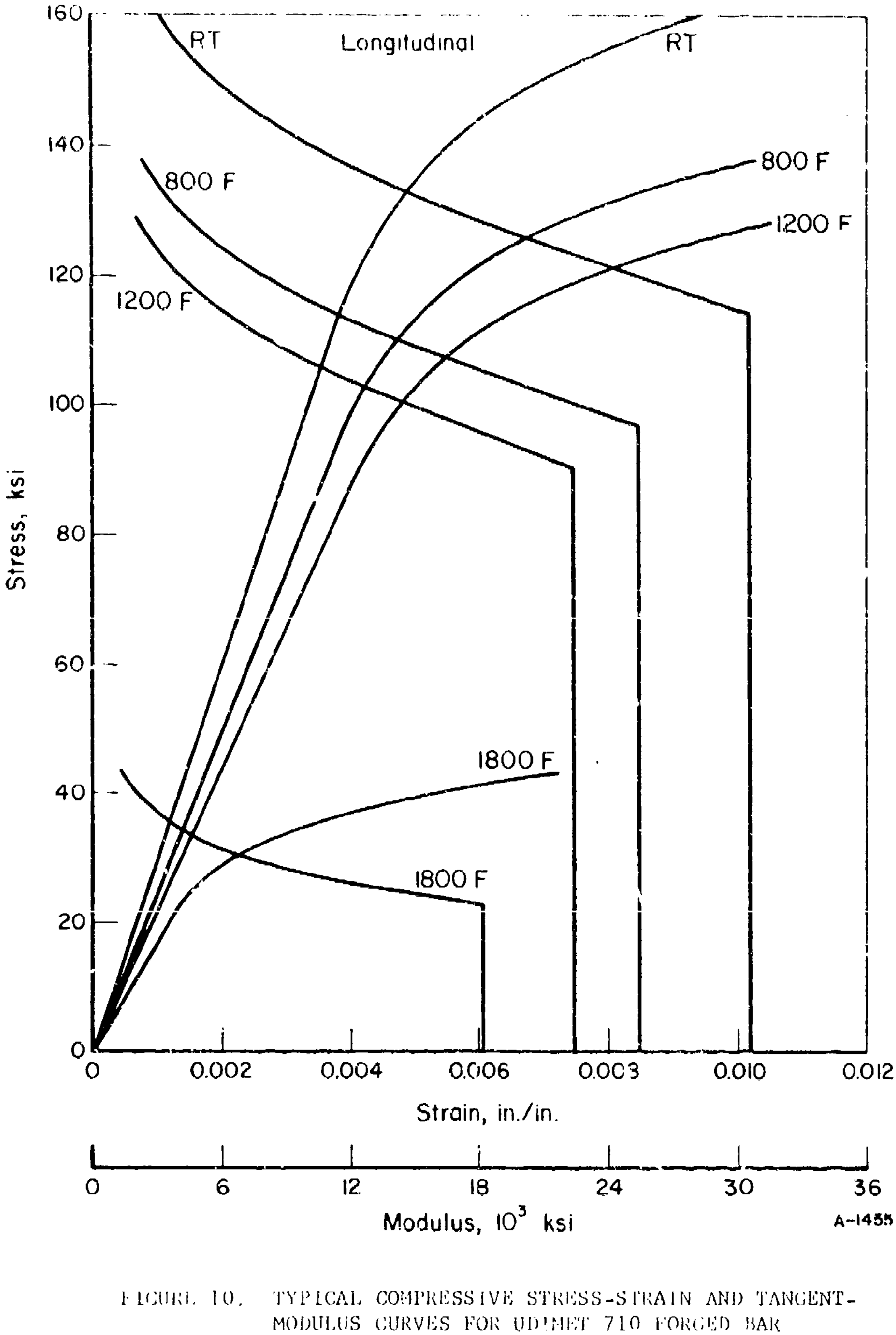

FIGURE 10. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT-MODULUS CURVES FOR UDIMET 710 FORGED BAR (LONGITUDINAL)

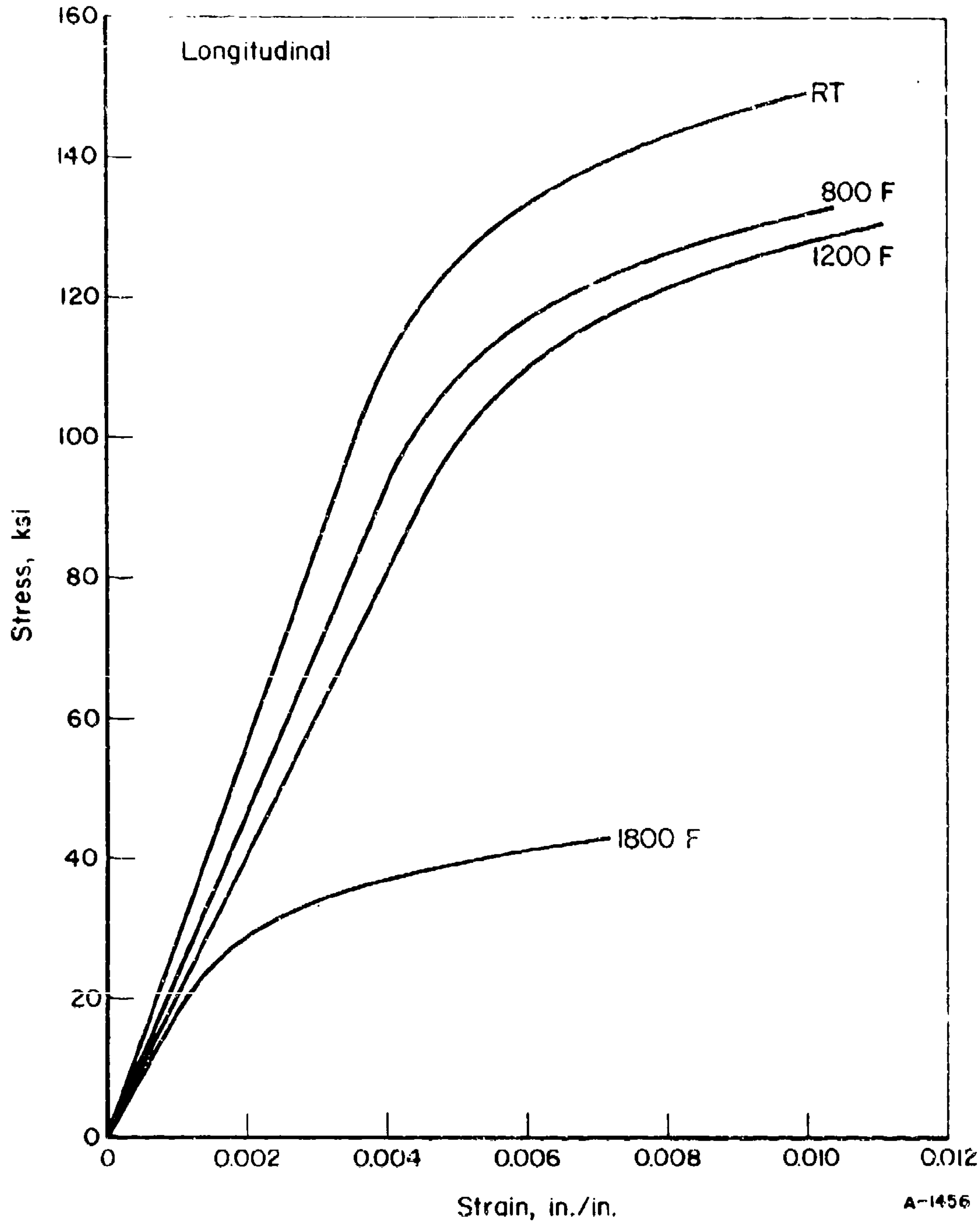

FIGURE 11. TYPICAL TENSILE STRESS-STRAIN CURVES FOR UDIMET 710 FORGED BAR (LONGITUDINAL)

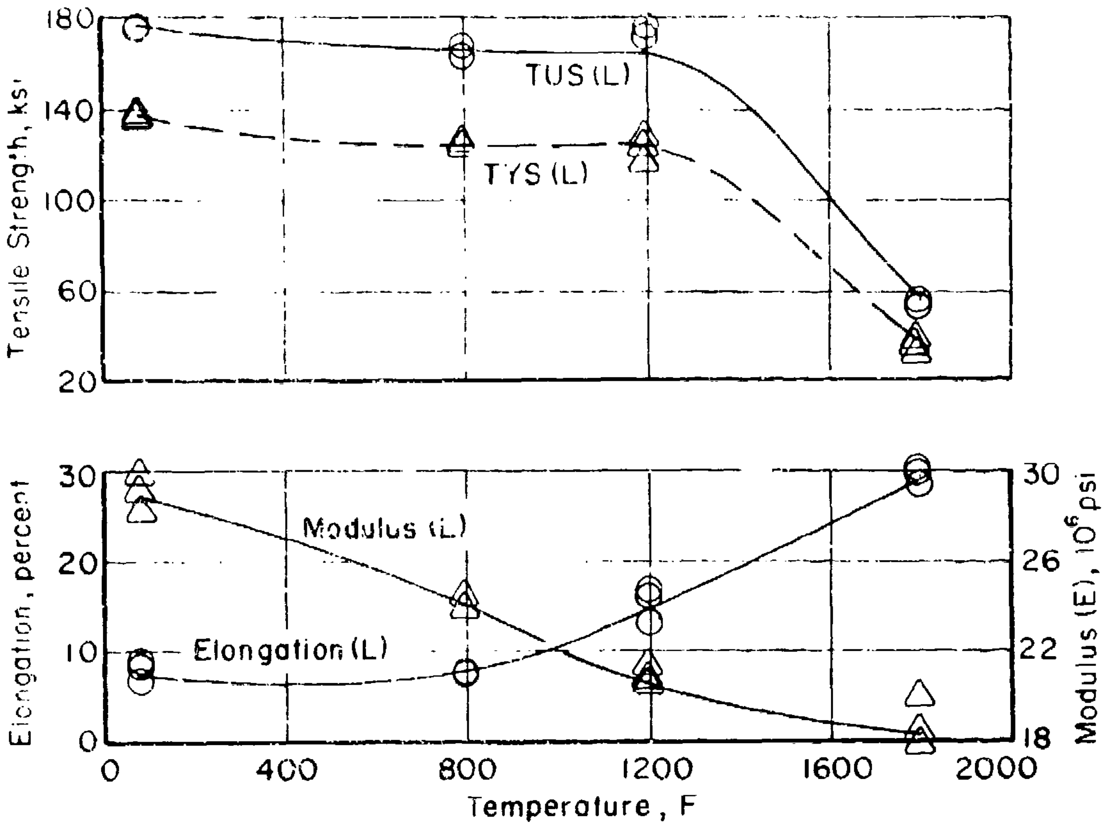

FIGURE 12. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF UDIMET 710 FORGED BAR

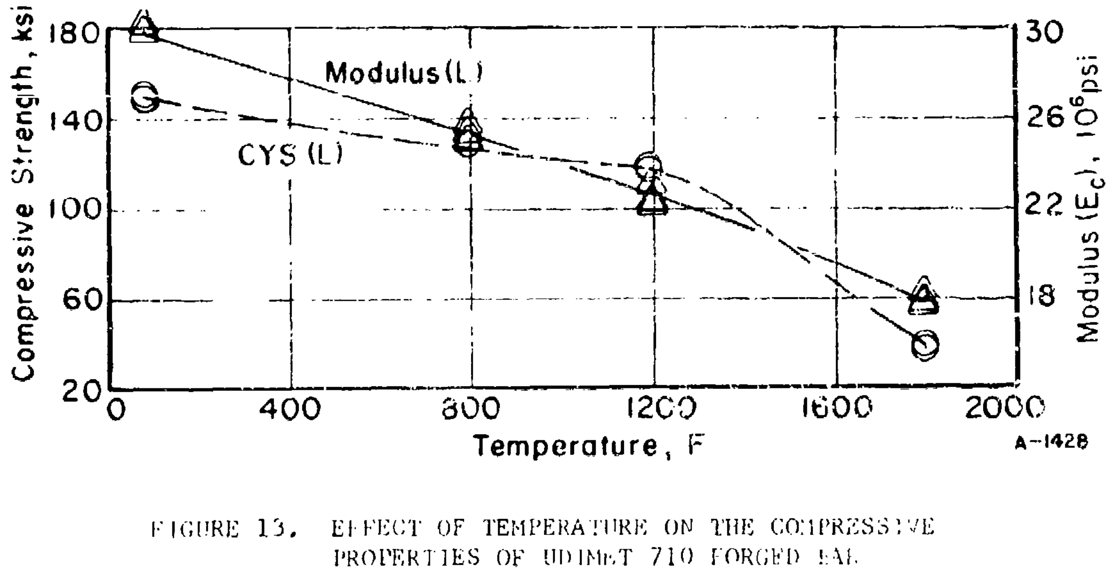

FIGURE 13. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF UDIMET 710 FORGED BAR

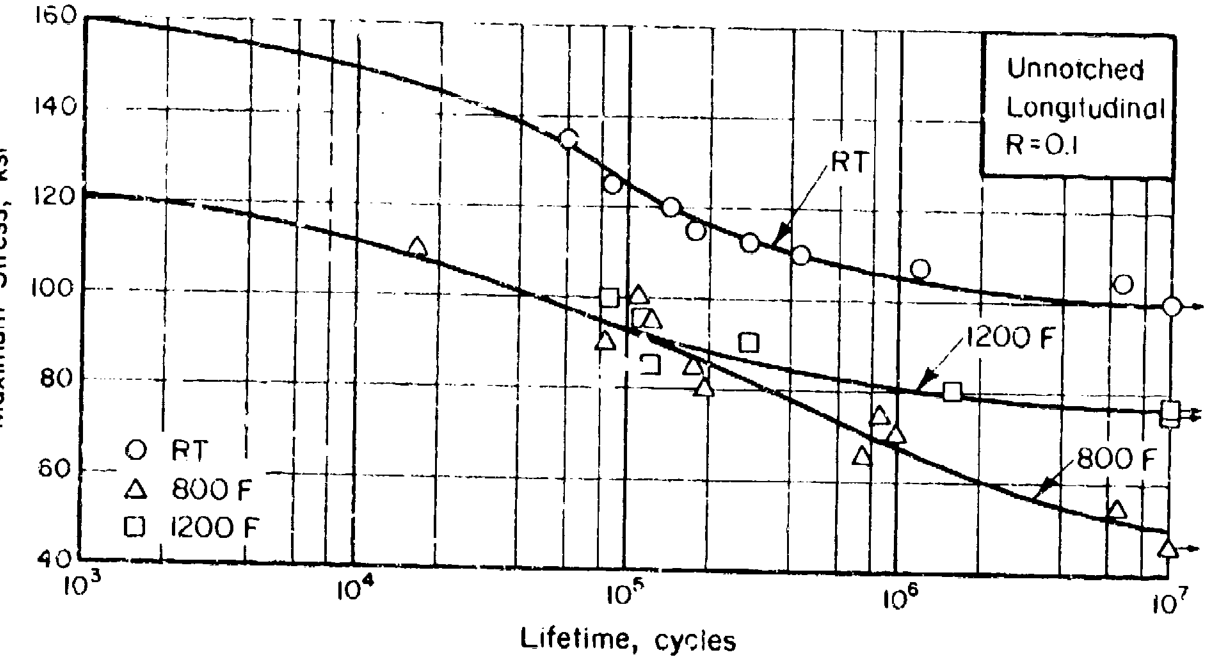

FIGURE 14. AXIAL LOAD FATIGUE RESULTS FOR UNNOTCHED UDIMET 710 FORGED BAR

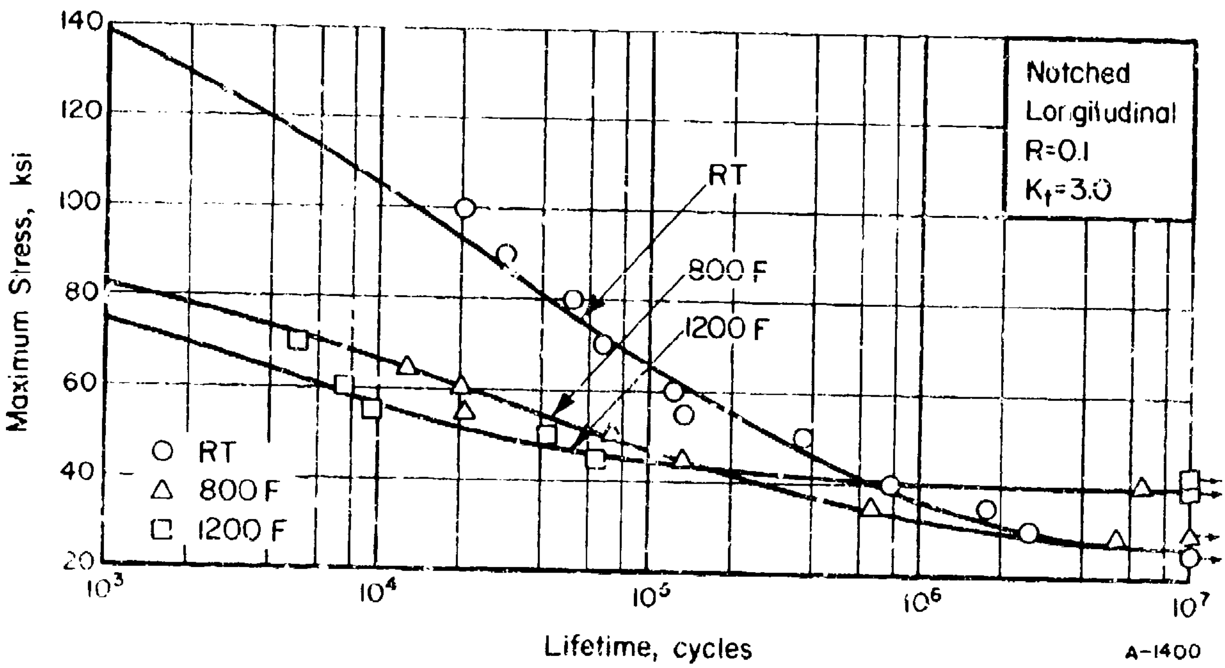

FIGURE 15. AXIAL LOAD FATIGUE RESULTS FOR NOTCHED (K_t = 3.0) UDIMET 710 FORGED BAR

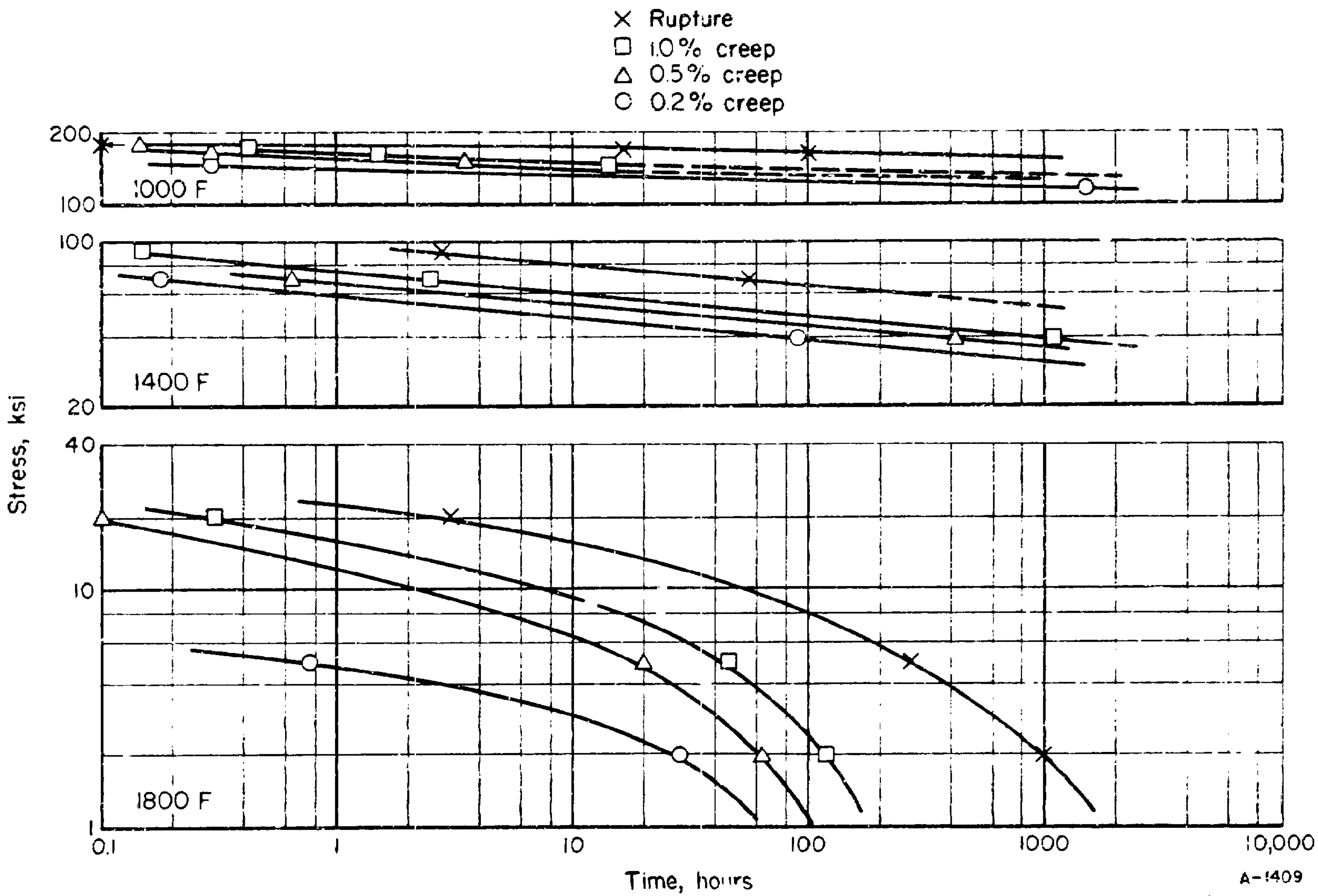

FIGURE 16. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR UDIMET 710 FORGED BAR

7050-T7E56 Hand Forging

Material Description

Alloy 7050 is an Al-Zn-Mg-Cu alloy developed by the Alcoa Research Laboratories supported by the Naval Air Systems Command and the Air Force Materials Laboratory. When heat treated and aged to the -T73 temper, thick 7050 plate and hand forgings exhibit strengths equal to or exceeding those of 7079-T6XX products combined with improved fracture toughness and a high resistance to exfoliatiation and stress-corrosion cracking. The alloy differs from conventional 7XXX series aluminum alloys in that zirconium is added and chromium and manganese are restricted in order to minimize quench sensitivity.

The material used for this evaluation was a 5-inch by 10-inch by 5-foot hand forging produced within the following composition limits:

Chemical Composition	Percent
Copper	2.0 to 2.8
Iron	0.15 max
Silicon	0.12 max
Manganese	0.10 max
Magnesium	1.9 to 2.6
Zinc	5.7 to 6.7
Chromium	0.04 max
Titanium	0.06 max
Aluminum	Balance

Processing and Heat Treating

The specimens were tested in the as-received -T7E56 temper.

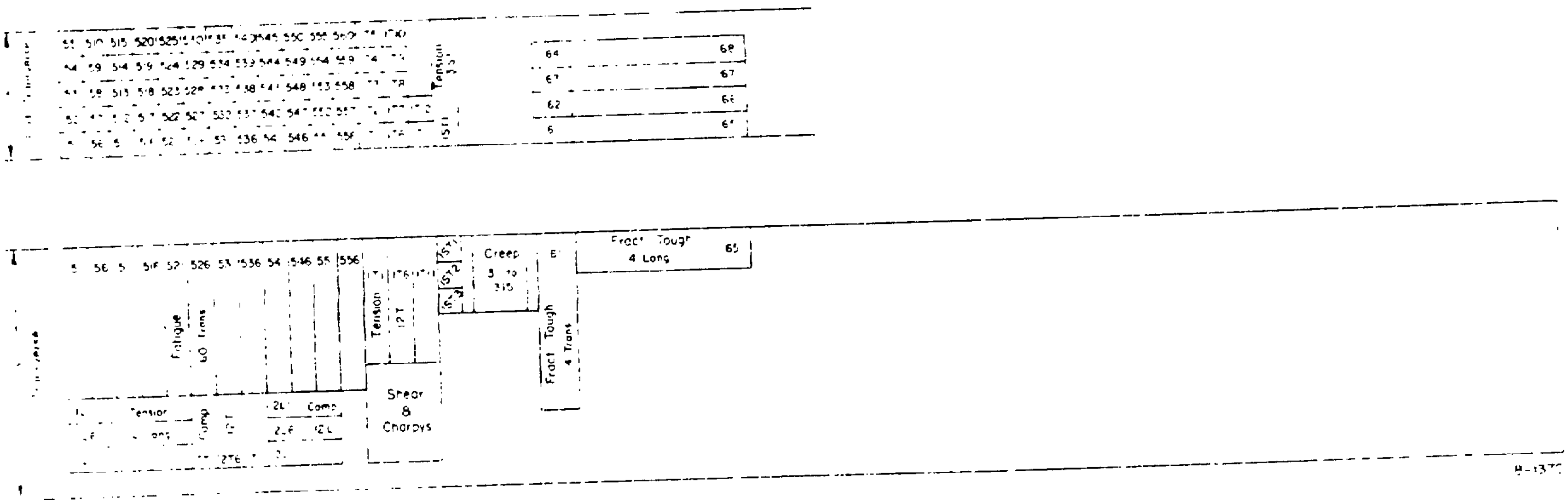

FIGURE 17. SPECIMEN LAYOUT FOR 7050-T7E56 HAND FORGING

Test Results

Tension. Results of tests in the longitudinal and transverse directions at room temperature, 250 F, 350 F, and 500 F are given in Table XVII. Short transverse tests were not conducted at elevated temperatures. Stress-strain curves at temperature are presented in Figures 18 and 19. Effect of temperature curves are shown in Figure 22.

Compression. Results of tests in both the longitudinal and transverse directions at room temperature, 250 F, 350 F, and 500 F are given in Table XVIII. Stress-strain and tangent-modulus curves at temperature are presented in Figures 20 and 21. Effect of temperature curves are shown in Figure 23.

Shear. Pin shear test results for longitudinal and transverse specimens at room temperature are given in Table XIX.

Impact. Charpy test results for longitudinal and transverse specimens at room temperature are given in Table XX.

Fracture Toughness. Results of slow bend tests for longitudinal and transverse specimens are given in Table XXI. The transverse tests fall within the size ratio, $2.5\ (K_Q/TYS)^2$, and the K_Q values are considered valid. The longitudinal tests do not meet this requirement and are not considered valid by existing ASTM criteria.

Fatigue. Axial-load fatigue tests were conducted on transverse specimens at room temperature, 250 F, and 350 F. Tabular test results are given in Tables XXII and XXIII. S-N curves are shown in Figures 24 and 25.

Creep and Stress Rupture. Results of transverse tests at 250 F, 350 F, and 500 F are given in Table XXIV. Log-stress versus log-time curves are presented in Figure 26.

Stress Corrosion. Tests were conducted as described in the experimental procedures section of this report. No failures or cracks occurred in the 1000-hour test duration.

Thermal Expansion. The coefficient of thermal expansion for this alloy is 12.8×10^{-6} in./in./F for 68 F to 212 F.

Density. The density value for X7050 is 0.102 lb/in.^{3}.

TABLE XVII. TENSION TEST RESULTS FOR 7050-T7E56 HAND FORGING

Specimen No.	Ultimate Tensile Strength, ksi	0.2 Percent Offset Yield Strength, ksi	Elongation in 2 Inches, percent	Reduction in Area, percent	Tensile Modulus, 10^6 psi
		Longitudinal at Room Temperature			
1L-1	74-4	65.7	15.0	38.8	10.2
1L-2	73.7	63.4	15.0	38.1	9.9
1L-3	73.2	62.7	16.0	40.6	9.7
		Transverse at Room Temperature			
1T-1	74.0	64.4	9.0	13.0	9.9
1T-2	69.9	60.7	4.5	5.4	9.9
1T-3	69.4	61.2	3.5	5.1	9.9
		Short Transverse at Room Temperature			
1ST-1	70.4	56.7	6.0	7.0	9.6
1ST-2	71.8	58.3	5.5	6.0	9.9
1ST-3	74.0	61.7	7.5	10.6	9.8
		Longitudinal at 250 F			
1L-4	58.1	56.5	14.0	48.0	9.5
1L-5	56.4	54.5	21.0	52.1	9.7
1L-6	57.4	55.2	13.5	43.6	9.3
		Transverse at 250 F			
1T-4	57.3	55.7	22.0	54.0	9.4
1T-5	59.0	57.1	13.0	31.4	9.6
1T-6	56.0	52.8	12.5	21.2	9.3
		Longitudinal at 350 F			
1L-7	47.4	46.7	15.0	62.7	8.3
1L-8	45.9	44.8	17.0	60.7	8.3
1L-9	48.0	47.4	14.0	62.2	8.4

TABLE XVII. (Continued)

Specimen No.	Ultimate Tensile Strength, ksi	0.2 Percent Offset Yield Strength, ksi	Elongation in 2 Inches, percent	Reduction in Area, percent	Tensile Modulus, 10^6 psi
			Transverse at 350 F		
1T-7	44.2	42.8	18.5	58.0	8.9
1T-8	45.9	44.3	15.0	44.2	8.1
1T-9	46.4	44.3	14.5	37.8	8.2
			Longitudinal at 500 F		
1L-10	18.7	18.4	23.0	72.4	8.8
1L-11	19.9	19.7	24.5	85.5	7.8
1L-12	17.2	17.0	38.5	89.5	8.3
			Transverse at 500 F		
1T-10	19.7	18.7	23.5	80.2	7.8
1T-11	19.3	19.0	27.0	84.6	8.3
1T-12	19.2	18.5	25.0	77.6	7.6

TABLE XVIII. COMPRESSION TEST RESULTS FOR 7050-T7E56 HAND FORGING

Specimen No.	0.2 Percent Offset Yield Strength, ksi	Compressive Modulus, 10^6 psi
	Longitudinal at Room Temperature	
2L-1	69.4	10.5
2L-2	71.4	10.9
2L-3	64.8	10.7
	Transverse at Room Temperature	
2T-1	65.3	12.2
2T-2	66.3	11.0
2T-3	65.3	11.0
	Longitudinal at 250 F	
2L-4	60.7	9.9
2L-5	62.3	10.1
2L-6	60.9	9.8
	Transverse at 250 F	
2T-4	57.6	9.3
2T-5	59.3	9.9
2T-6	59.8	9.8
	Longitudinal at 350 F	
2L-7	51.2	9.3
2L-8	50.0	9.1
2L-9	50.1	9.2
	Transverse at 350 F	
2T-7	49.4	9.0
2T-8	49.6	9.4
2T-9	49.6	8.9

TABLE XVIII. (Continued)

Specimen No.	0.2 Percent Offset Yield Strength, ksi	Compressive Modulus, 10^6 psi
	Longitudinal at 500 F	
2L-10	20.7	7.6
2L-11	21.5	6.7
2L-12	21.5	7.5
	Transverse at 500 F	
2T-10	20.8	6.6
2T-11	21.5	6.6
2T-12	22.2	7.9

TABLE XIX. SHEAR TEST RESULTS FOR 7050-T7E56 HAND FORGING AT ROOM TEMPERATURE

Specimen Number	Ultimate Shear Strength, ksi
Longitudinal	
4L-1	41.3
4L-2	42.5
4L-3	44.6
4L-4	43.6
Transverse	
4T-1	40.5
4T-2	40.0
4T-3	42.8
4T-4	43.1

TABLE XX. IMPACT TEST RESULTS FOR 7050-T7E56 HAND FORGING AT ROOM TEMPERATURE

Specimen No.	Energy, ft-lb
Longitudinal	
10L-1	15.0
10L-2	7.0
10L-3	13.5
10L-4	8.0
10L-5	10.0
10L-6	14.5
Transverse	
10T-1	2.0
10T-2	2.0
10T-3	2.0
10T-4	2.0
10T-5	2.0
10T-6	2.5

TABLE XXI. FRACTURE TOUGHNESS TEST RESULTS FOR 7050-T7E56 HAND FORGING

Specimen Number	W, inches	a, inches	T, inches	P, lbs	Span, inches	$f(\frac{a}{W})$	K_Q
			Transverse				
2T	1.501	.837	.750	1,750	6	3.2	24.6 (a)
3T	1.502	.863	.751	2,000	6	3.4	29.8 (a)
4T	1.502	.875	.750	2,200	6	3.5	33.8 (a)
1T	1.502	.837	.751	1,940	6	3.2	27.2 (a)
			Longitudinal				
6L	1.501	.861	.751	3,800	6	3.4	56.6 (b)
8L	1.502	.896	.750	4,000	6	3.7	64.8 (b)
5L	1.500	.859	.750	3,510	6	3.4	52.2 (b)
7L	1.501	.898	.750	4,700	6	3.7	76.8 (b)

(a) Candidate fracture toughness values, K_Q, are valid valid K_{Ic} values.

(b) Candidate fracture toughness values, K_Q, are invalid as K_{Ic} values since a, T, $<2.5 \left(\frac{K_Q}{TYS}\right)^2$.

TABLE XXII. AXIAL LOAD FATIGUE TEST RESULTS FOR UNNOTCHED 7050-T7E56 HAND FORGING (TRANSVERSE)

Specimen Number	Maximum Stress, ksi	Lifetime cycles
	Room Temperature	
5-2	55.0	36,800
5-23	52.5	200
5-1	50.0	39,630
5-3	45.0	80,380
5-21	42.5	11,500
5-4	40.0	248,480
5-22	37.5	258,000
5-5	35.0	393,210
5-24	32.5	406,000
5-6	30.0	12,465,500[a]
	250 F	
5-7	55.0	100
5-8	50.0	117
5-12	40.0	20,600
5-9	35.0	36,590
5-10	30.0	76,480
5-11	25.0	2,725,100
5-26	22.5	10,137,580[a]
5-13	20.0	11,369,800[a]
	350 F	
5-14	40.0	100
5-20	40.0	10,100
5-17	35.0	16,650
5-15	30.0	50,670
5-16	25.0	122,250
5-18	20.0	121,930
5-25	17.5	20,713,500[a]
5-19	15.0	10,167,600[a]

(a) Did not fail.

TABLE XXIII. AXIAL LOAD FATIGUE TEST RESULTS FOR NOTCHED (K_t = 3.0) 7050-T7E56 HAND FORGING (TRANSVERSE)

Specimen Number	Maximum Stress, ksi	Lifetime, cycles
	Room Temperature	
5-1	35.0	15,120
5-2	30.0	22,380
5-3	25.0	36,300
5-21	22.5	57,500
5-4	20.0	170,130
5-20	17.5	195,100
5-5	15.0	553,750
5-22	12.5	12,753,700(a)
5-6	10.0	10,781,080(a)
	250 F	
5-8	30.0	19,060
5-23	27.5	214,800
5-7	25.0	185,550
5-24	22.5	214,800
5-9	20.0	272,550
5-11	17.5	191,680
5-10	15.0	788,020
5-12	13.5	10,622,140(a)
	350 F	
5-13	30.0	10,860
5-14	25.0	39,200
5-15	22.5	29,460
5-16	20.0	72,910
5-17	17.5	267,530
5-18	15.0	160,430
5-25	15.0	1,161,700
5-19	13.5	12,207,520(a)

(a) Did not fail.

TABLE XXIV. SUMMARY DATA ON CREEP AND RUPTURE PROPERTIES FOR 7050-T7E56 HAND FORGING (TRANSVERSE)

Specimen No.	Stress, ksi	Temp, F	Hours to Indicated Creep Deformation, percent					Initial Strain, percent	Rupture Time, hr	Elongation in 2 in., percent	Reduction of Area, percent	Minimum Creep Rate, percent/hr
			0.1	0.2	0.5	1.0	2.0					
3-1	50	250	0.11	0.35	1.7	4.7	---	0.677	18.3	11.1	33.7	0.15
3-3	40	250	10	75	355	545	---	0.422	668.4	2.2	2.6	0.001
3-10	35	250	208	805	2570(b)	---	---	0.389	863.4(a)	0.600	--	0.0007
3-2	25	350	3.1	8.8	27	---	---	0.289	50.2	14.8	56.7	0.017
3-5	15	350	50	125	300	446	582	0.107	668.4	8.9	18.6	0.0019
3-11	11	350	620	1000(b)	---	---	---	0.185	765.1(a)	0.315	--	0.00016
3-4	7	500	0.4	1.3	6.4	15.6	26.8	0.122	48.2	31.1	68.3	0.052
3-6	5.3	500	6.0	12	34	75	128	0.167	229.6	13.3	47.1	0.0093
3-7	4.2	500	20	60	180	265	390	0.078	691.5	12.6	35.6	0.0051
3-8	3.0	500	15	80	550(b)	---	---	0.070	167.1(a)	0.348	--	0.0055
3-9	1.5	500	1550	3450(b)	7200(b)	---	---	0	905.8(a)	0.067	--	0.000053

(a) Test discontinued.
(b) Estimate.

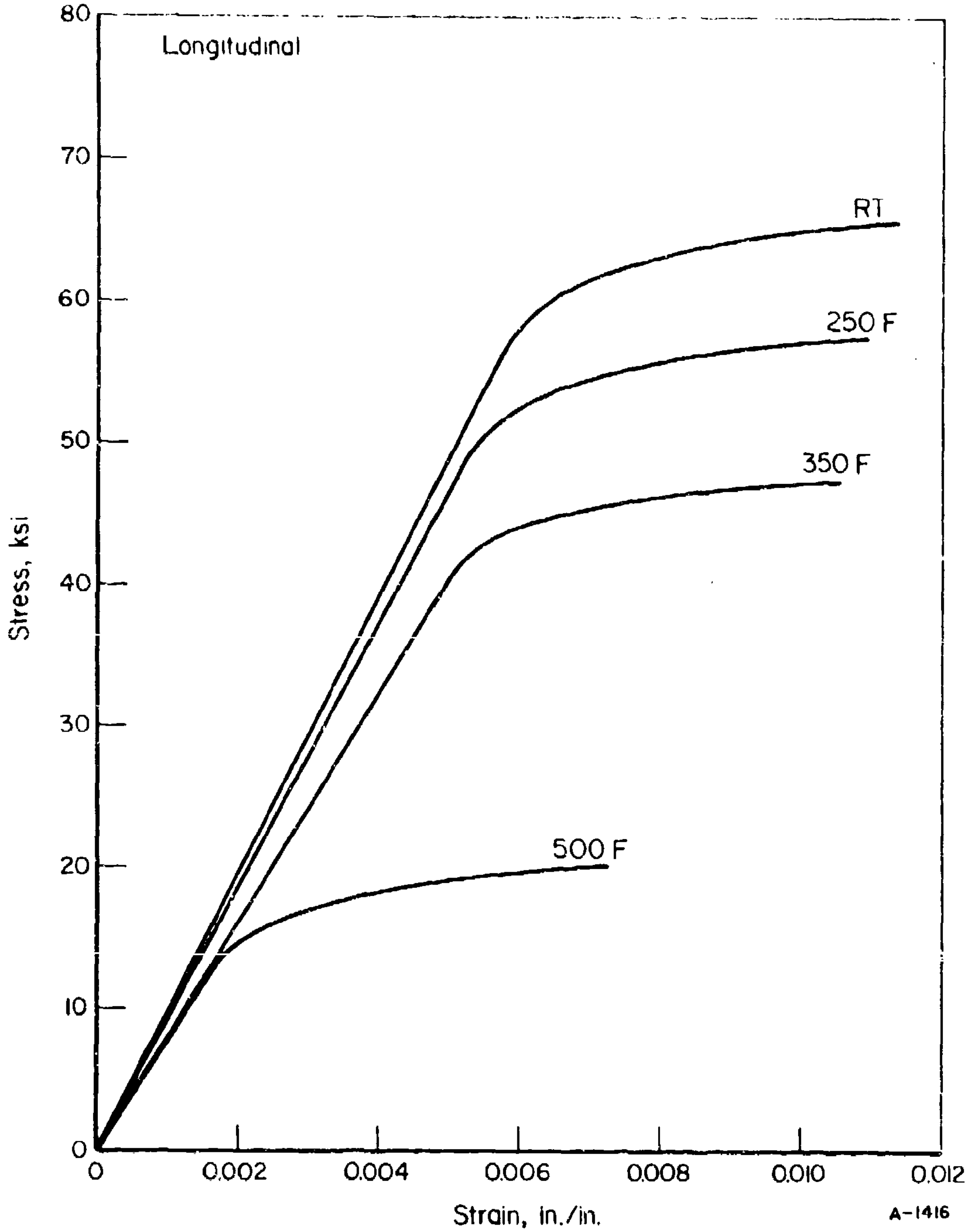

FIGURE 18. TYPICAL TENSILE STRESS-STRAIN CURVES FOR 7050-T7E56 HAND FORGING (LONGITUDINAL)

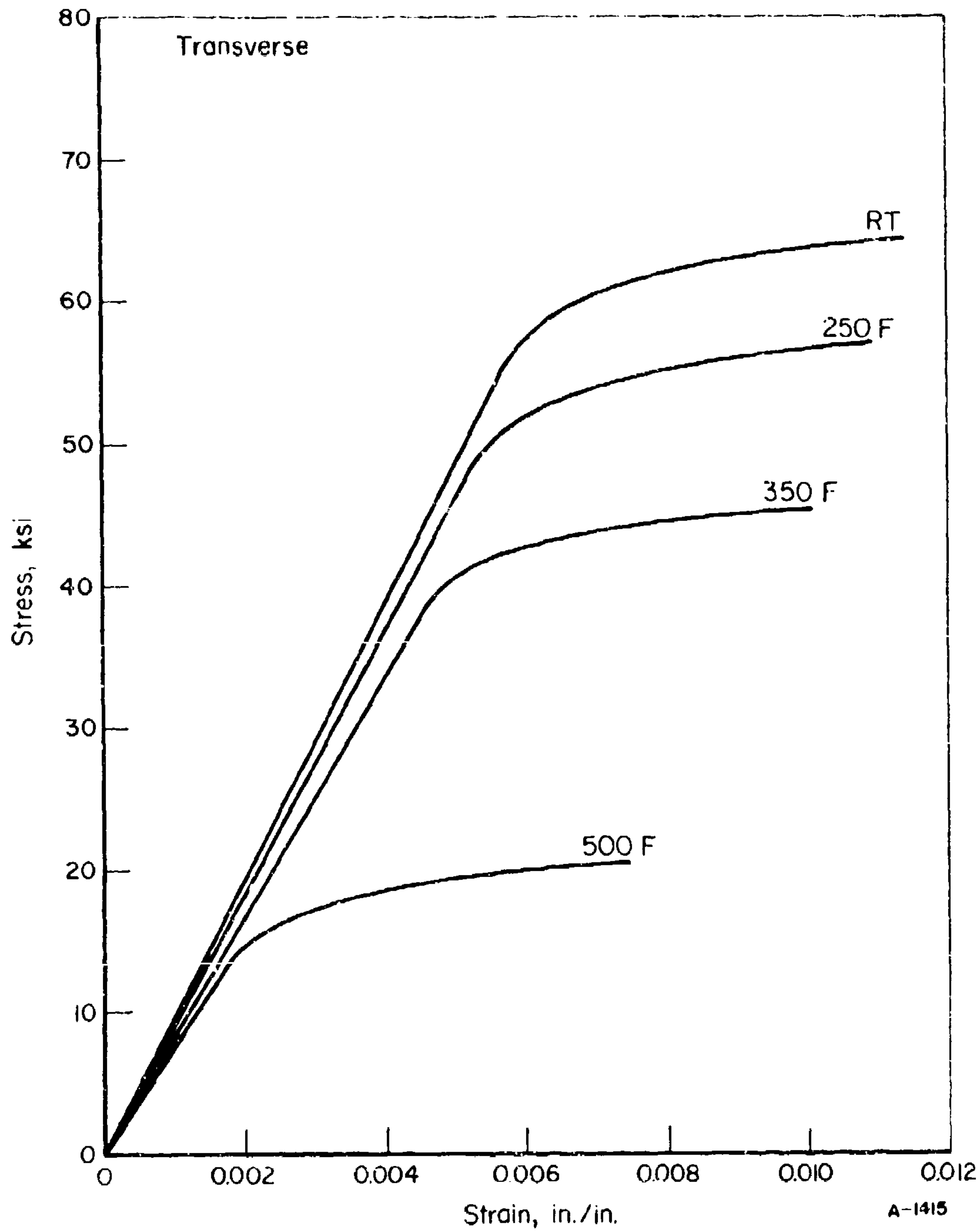

FIGURE 19. TYPICAL TENSILE STRESS-STRAIN CURVES FOR 7050-T7E56 HAND FORGING (TRANSVERSE)

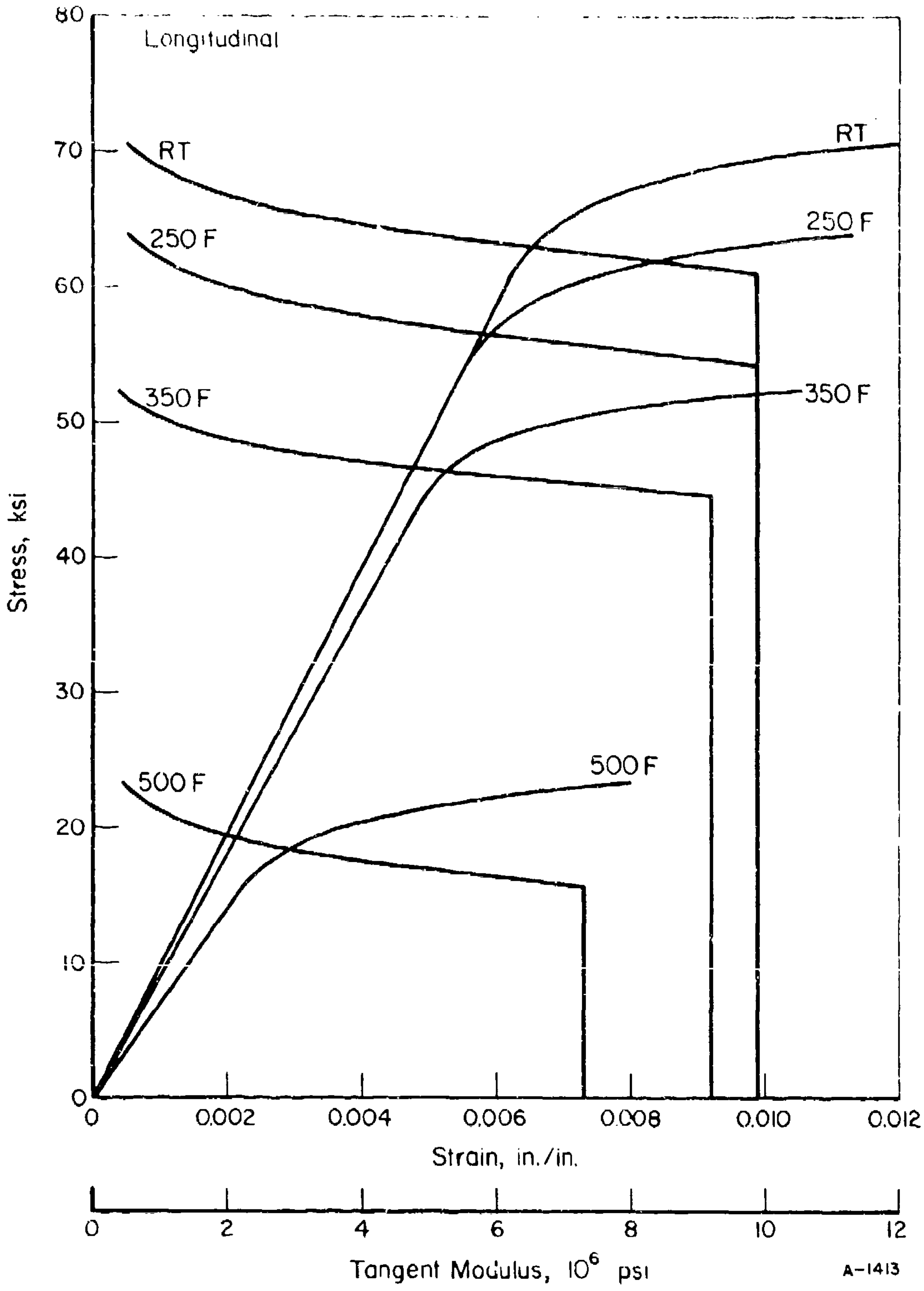

FIGURE 20. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT MODULUS CURVES FOR 7050-T7E56 HAND FORGING (LONGITUDINAL)

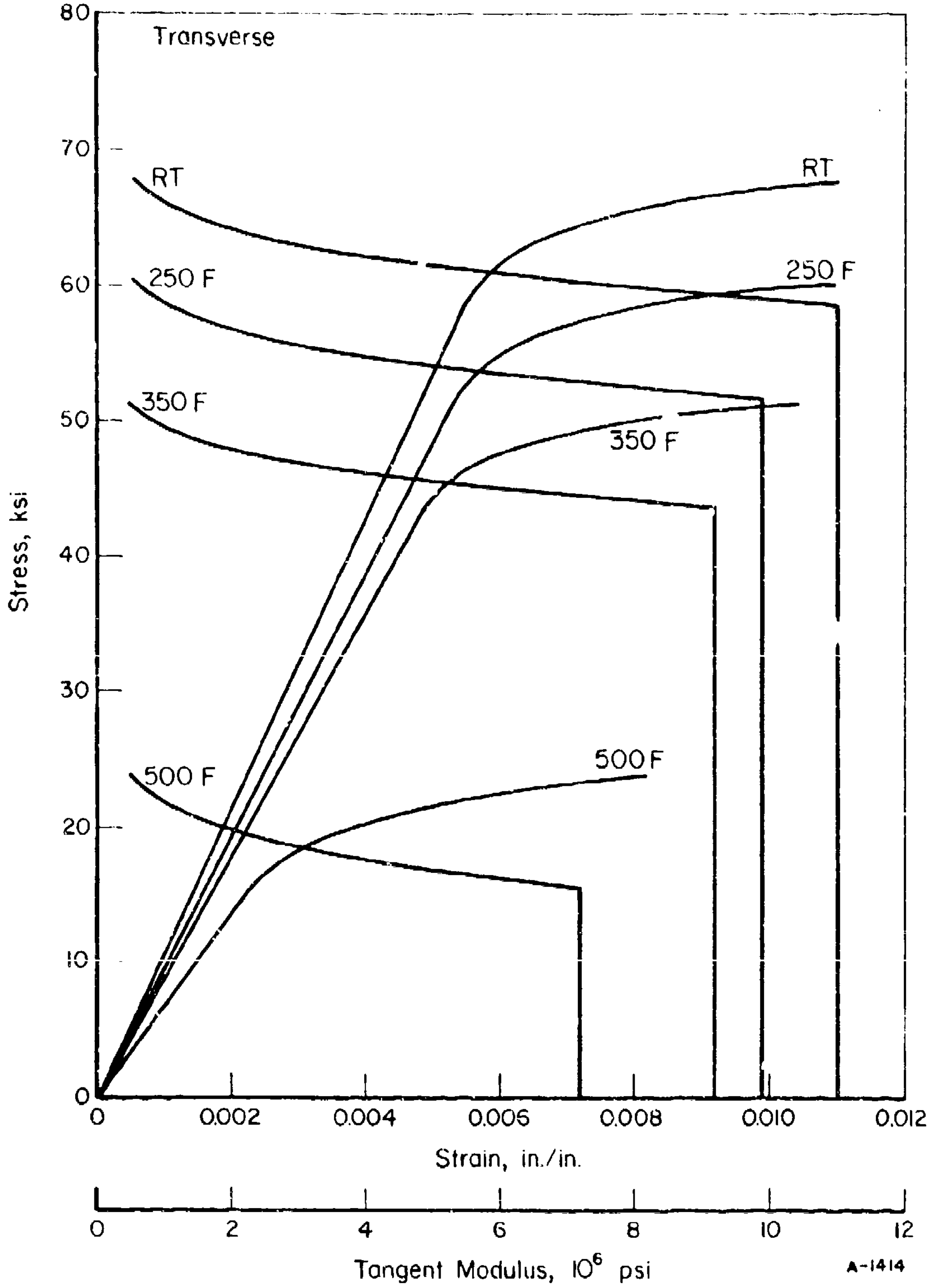

FIGURE 21. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT MODULUS CURVES FOR 7050-T7E56 HAND FORGING (TRANSVERSE)

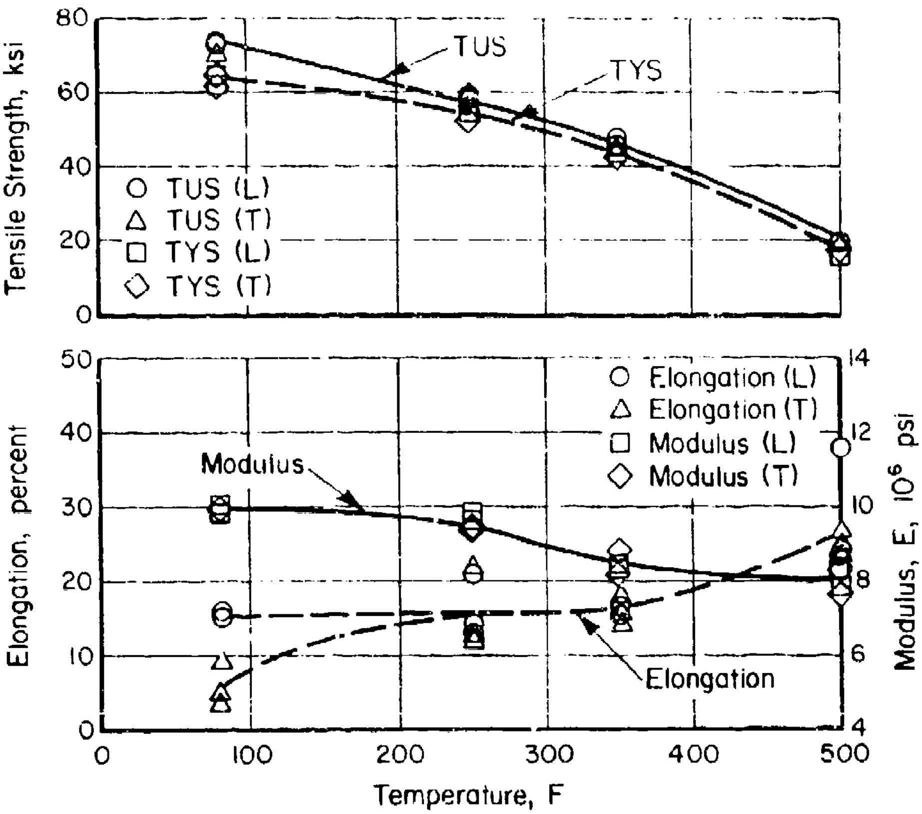

FIGURE 22. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF 7050-T7E56 HAND FORGING

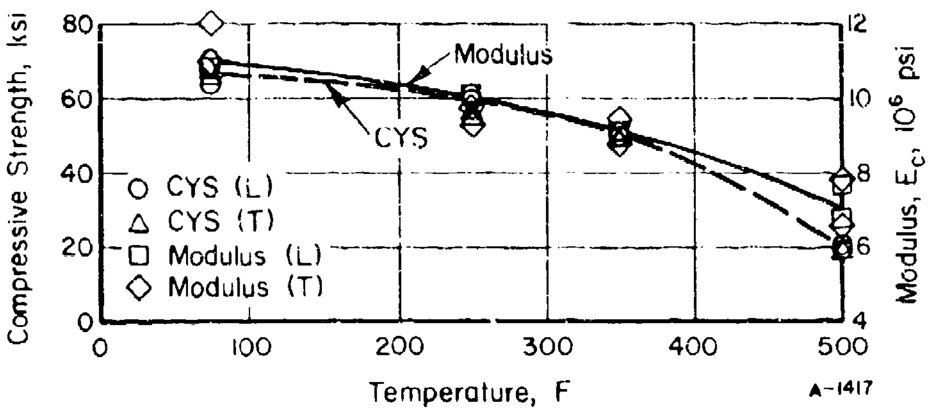

FIGURE 23. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF 7050-T7E56 HAND FORGING

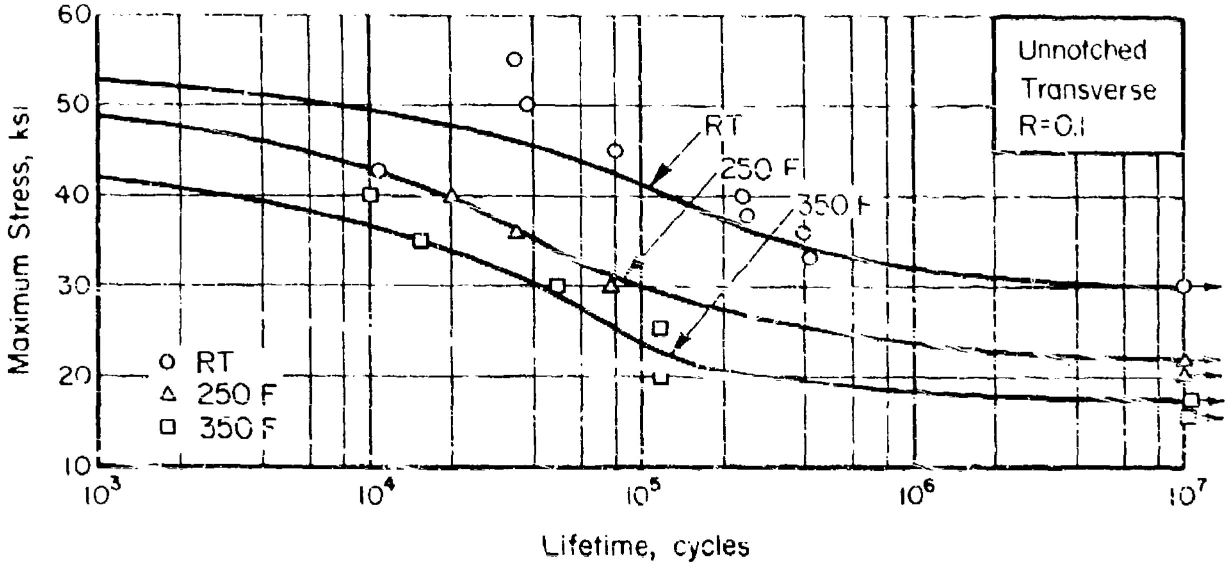

FIGURE 24. AXIAL-LOAD FATIGUE RESULTS FOR UNNOTCHED 7050-T7E56 HAND FORGING

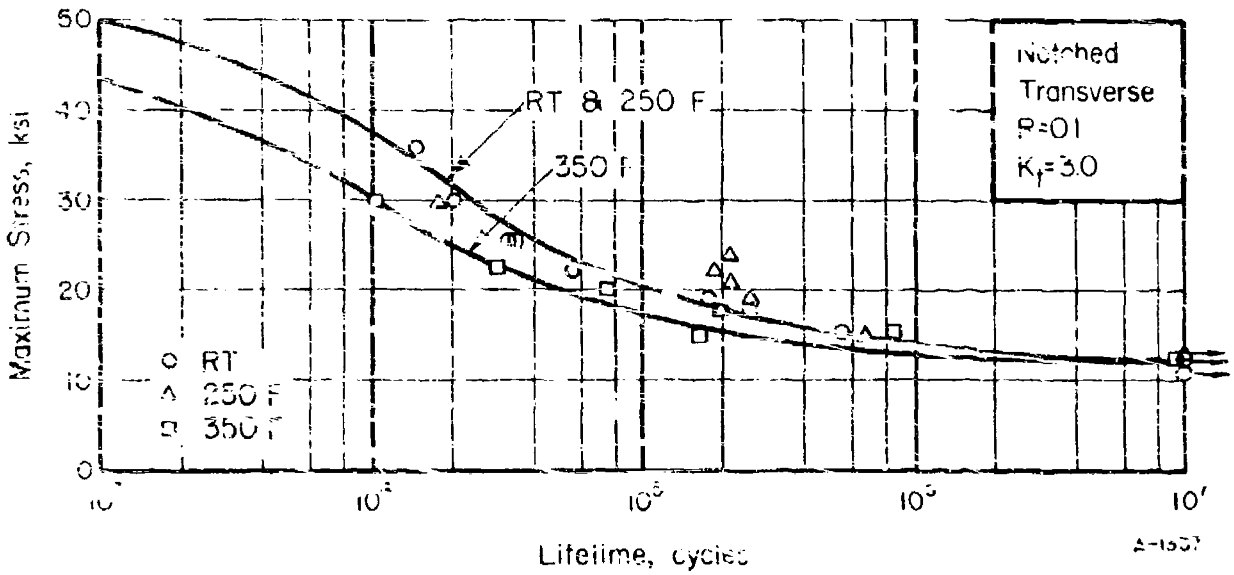

FIGURE 25. AXIAL-LOAD FATIGUE RESULTS FOR NOTCHED (K_t = 3.0) 7050-T7E56 HAND FORGING

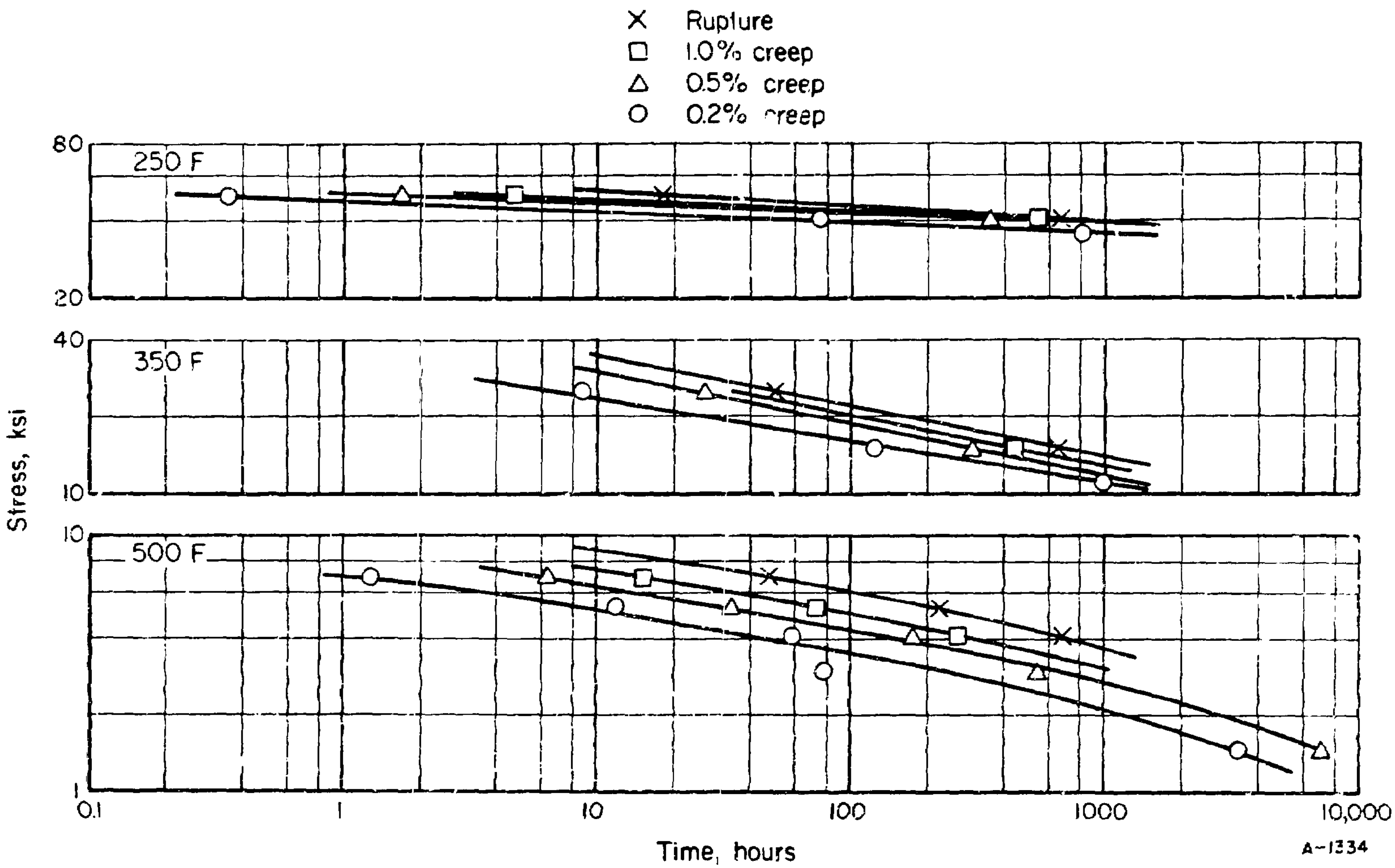

FIGURE 26. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR 7050-T7E56 HAND FORGING (TRANSVERSE)

2214-T351 Plate (Alcoa 417 Process)

Material Description

Alloy 2214 is a high-purity version of 2014 with closer controls on iron and silicon (Alcoa 417 process). The Alcoa 417 process, which utilizes only hot rolling and special controls during all stages of fabrication, is a more economic means for achieving the required properties without adversely influencing the overall engineering characteristics of the material. The material used in this evaluation was obtained from Alcoa as a 2-1/4-inch-thick plate within the following composition limits:

Chemical Composition	Percent
Silicon	0.50 to 1.2
Iron	0.3 max
Copper	3.9 to 5.0
Manganese	0.40 to 1.2
Magnesium	0.20 to 0.80
Chromium	0.10 max
Zinc	0.25 max
Titanium	0.15
Others	0.15 max
Aluminum	Balance

Processing and Heat Treating

The specimen layout for 2214 is shown in Figure 27. Specimens were tested in the as-received -T351 temper.

Test Results

Tension. Results of longitudinal and transverse tests at room temperature, 250 F, 350 F, and 500 F are given in Table XXV. Stress-strain curves at temperature are presented in Figures 28 and 29. Effect of temperature curves are shown in Figure 32.

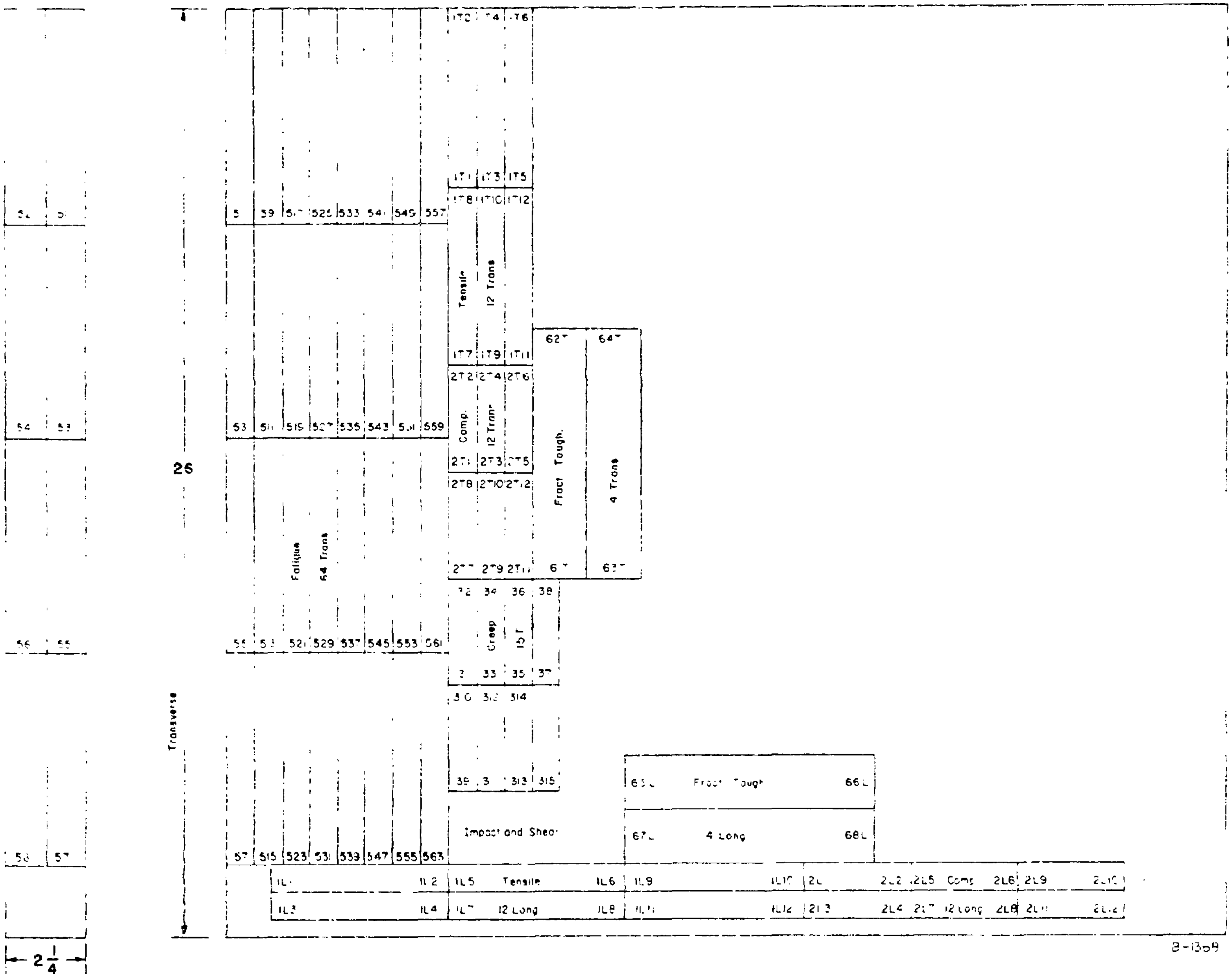

FIGURE 27. SPECIMEN LAYOUT FOR 2214-T351 PLATE

Compression. Results of longitudinal and transverse tests at room temperature, 250 F, 350 F, and 500 F are given in Table XXVI. Stress-strain and tangent modulus curves at temperature are presented in Figures 30 and 31. Effect of temperature curves are shown in Figure 33.

Shear. Pin shear test results for longitudinal and transverse specimens at room temperature are given in Table XXVII.

Impact. Charpy test results for longitudinal and transverse specimens are given in Table XXVIII.

Fracture Toughness. Slow bend tests were conducted on longitudinal and transverse specimens at room temperature. The size ratio, 2.5 $(K_Q/TYS)^2$, was greater than both the specimen thickness and crack length in all tests; therefore, the K_Q values given in the table are not considered valid K_{Ic} values by existing ASTM criteria. These data are shown in Table XXIX.

Fatigue. Axial-load fatigue test results for transverse specimens, both unnotched and notched, at room temperature, 250 F, and 350 F are given in Tables XXX and XXXI. S-N curves are presented in Figures 34 and 35.

Creep and Stress Rupture. Results of transverse specimen tests at 250 F, 350 F, and 500 F are given in Table XXXII. Log-stress versus log-time curves are presented in Figure 36.

Stress Corrosion. Tests were conducted as described in the experimental procedures section of this report. No failures or cracks occurred in the 1000-hour test duration.

Thermal Expansion. The coefficient of thermal expansion for this alloy is 13.5 x 10^{-6} in./in./F for 68 F to 500 F.

Density. The density of this material is 0.101 lb/in.^{3}.

TABLE XXV. TENSION TEST RESULTS FOR 2214-T351 PLATE

Specimen No.	Ultimate Tensile Strength, ksi	0.2 Percent Offset Yield Strength, ksi	Elongation in 2 Inches, percent	Reduction in Area, percent	Tensile Modulus, 10^6 psi
		Longitudinal at Room Temperature			
1L-1	65.2	46.9	24.0	34.7	10.4
1L-2	64.7	46.5	24.0	35.7	10.5
1L-3	64.9	46.9	23.5	32.1	10.5
		Transverse at Room Temperature			
1T-1	66.0	42.3	20.5	28.5	10.5
1T-2	65.9	43.5	20.5	27.7	10.7
1T-3	66.0	42.3	22.0	26.7	10.4
		Longitudinal at 250 F			
1L-4	56.0	42.0	20.0	34.0	10.0
1L-5	56.0	41.7	24.0	48.0	9.8
1L-6	56.4	41.6	23.0	37.0	9.8
		Transverse at 250 F			
1T-4	57.0	39.2	28.5	31.4	9.7
1T-5	56.4	38.2	21.0	34.5	9.6
1T-6	58.2	37.9	22.0	34.7	10.0
		Longitudinal at 350 F			
1L-7	52.0	38.0	24.0	62.7	9.6
1L-8	51.0	36.9	23.5	60.0	9.3
1L-9	52.0	38.0	25.0	60.0	9.[illegible]
		Transverse at 350 F			
1T-7	53.0	36.0	20.0	44.0	8.9
1T-8	53.0	36.0	21.0	37.8	9.7
1T-9	53.5	35.6	22.0	44.0	8.7

TABLE XXV. (Continued)

Specimen No.	Ultimate Tensile Strength, ksi	0.2 Percent Offset Yield Strength, ksi	Elongation in 2 Inches, percent	Reduction in Area, percent	Tensile Modulus, 10^6 psi
		Longitudinal at 500 F			
1L-10	26.0	20.0	26.0	72.4	8.0
1L-11	26.0	20.0	22.0	70.0	8.0
1L-12	26.4	19.0	27.0	72.0	8.1
		Transverse at 500 F			
1T-10	27.0	19.0	20.4	65.0	7.6
1T-11	26.4	18.7	20.0	68.0	8.2
1T-12	27.0	17.6	24.0	60.0	8.0

TABLE XXVI. COMPRESSION TEST RESULTS FOR 2214-T351 PLATE

Specimen No.	0.2 Percent Offset Yield Strength, ksi	Compressive Modulus, 10^6 psi
	Longitudinal at Room Temperature	
2L-1	38.3	9.6
2L-2	37.4	11.3
2L-3	37.5	11.2
	Transverse at Room Temperature	
2T-1	44.2	11.2
2T-2	44.9	10.3
2T-3	44.8	10.0
	Longitudinal at 250 F	
2L-4	35.6	9.6
2L-5	35.4	10.0
2L-6	35.7	10.1
	Transverse at 250 F	
2T-4	40.0	10.1
2T-5	40.6	10.2
2T-6	39.2	9.8
	Longitudinal at 350 F	
2L-7	32.0	8.9
2L-8	31.7	9.6
2L-9	32.0	8.6
	Transverse at 350 F	
2T-7	36.0	8.7
2T-8	35.0	9.0
2T-9	35.0	8.6

TABLE XXVI. (Continued)

Specimen No.	0.2 Percent Offset Yield Strength, ksi	Compressive Modulus, 10^6 psi
	Longitudinal at 500 F	
2L-10	25.0	7.1
2L-11	24.2	7.1
2L-12	26.0	7.0
	Transverse at 500 F	
2T-10	25.6	7.1
2T-11	26.0	7.1
2T-12	24.9	7.1

TABLE XXVII. SHEAR TEST RESULTS FOR 2214-T351 PLATE

Specimen Number	Ultimate Shear Strength, ksi
Longitudinal	
4L-1	39.0
4L-2	38.8
4L-3	41.1
4L-4	41.2
Transverse	
4T-1	38.7
4T-2	32.6
4T-3	38.6
4T-4	37.8

TABLE XXVIII. IMPACT TEST RESULTS FOR 2214-T351 PLATE

Specimen No.	Energy, ft-lb
Longitudinal	
10L-1	5.0
10L-2	6.0
10L-3	5.5
10L-4	4.0
Transverse	
10T-1	2.0
10T-2	1.5
10T-3	1.5
10T-4	2.5

TABLE XXIX. FRACTURE TOUGHNESS TEST RESULTS FOR 2214-T351 PLATE

Specimen Number	W, inches	a, inches	T, inches	P, lbs	Span, inches	$f(\frac{a}{W})$	K_Q (a)
			Transverse				
2T	1.500	.877	.750	3,200	6	3.57	49.7
3T	1.500	.906	.750	3,600	6	3.8	60.1
4T	1.500	.866	.750	3,400	6	3.4	51.4
1T	1.501	.845	.750	2,950	6	3.29	42.3
			Longitudinal				
6L	1.501	.880	.750	3,100	6	3.59	48.4
5L	1.501	.862	.751	3,100	6	3.4	46.2
7L	1.500	.819	.750	2,950	6	3.1	39.9
8L	1.500	.855	.750	3,100	6	3.38	45.6

(a) Candidate fracture toughness values, K_Q, are invalid as K_{Ic} values since a, T, $< 2.5 \left(\frac{K_Q}{TYS}\right)^2$.

TABLE XXX. AXIAL LOAD FATIGUE TEST RESULTS FOR UNNOTCHED 2214-T351 PLATE (TRANSVERSE)

Specimen Number	Maximum Stress, ksi	Lifetime, cycles
	Room Temperature	
5-2	70.0	(a)
5-4	60.0	12,210
5-3	55.0	39,870
5-1	50.0	67,850
5-23	47.5	147,100
5-5	45.0	301,330
5-6	40.0	4,042,880
5-7	35.0	13,127,900 (b)
	250 F	
5-9	50.0	14,800
5-8	45.0	52,700
5-10	40.0	95,800
5-11	35.0	230,400
5-12	30.0	221,400
5-13	25.0	10,475,800 (b)
	350 F	
5-19	47.5	(a)
5-15	45.0	74,860
5-16	40.0	63,350
5-20	37.5	82,650
5-17	35.0	146,790
5-18	30.0	11,717,600 (b)

(a) Failed on loading.

(b) Did not fail.

TABLE XXXI. AXIAL-LOAD FATIGUE TEST RESULTS FOR NOTCHED (K_t = 3.0) 2214-T351 PLATE (TRANSVERSE)

Specimen Number	Maximum Stress, ksi	Lifetime, cycles
	Room Temperature	
5-1	35.0	15,440
5-5	30.0	46,150
5-27	27.5	49,400
5-2	25.0	99,020
5-6	22.5	80,280
5-3	20.0	264,900
5-7	17.5	243,760
5-28	17.5	1,472,300
5-4	15.0	10,750,000[(a)]
	250 F	
5-17	35.0	33,000
5-18	30.0	35,850
5-19	25.0	59,230
5-20	22.5	82,440
5-21	20.0	124,730
5-22	17.5	98,450
5-23	15.0	429,900
5-24	13.5	592,100
5-25	13.5	3,795,900
5-26	11.0	10,390,110[(a)]
	350 F	
5-13	35.0	13,680
5-11	30.0	37,530
5-8	30.0	162,990
5-9	25.0	109,840
5-12	22.5	100,530
5-10	20.0	161,270
5-14	17.5	97,870
5-15	15.0	431,450
5-16	13.5	10,638,300[(a)]

(a) Did not fail.

TABLE XXXII. SUMMARY DATA ON CREEP AND RUPTURE PROPERTIES FOR 2214-T351 PLATE (TRANSVERSE)

Specimen No.	Stress, ksi	Temp, F	Hours to Indicated Creep Deformation, percent					Initial Strain, percent	Rupture Time, hr	Elongation in 2 in., percent	Reduction of Area, percent	Minimum Creep Rate, percent/hr
			0.1	0.2	0.5	1.0	2.0					
31	50	250	0.2	0.7	2.7	6.4	---	0.592	20.7	11.1	43.0	0.14
33	40	250	10	50	183	322	450	0.469	580.4	14.1	48.7	0.0018
36	35	250	40	145	---	---	---	0.459	264.3[a]	0.726	--	--
39	30	250	50	350	1670[b]	---	---	0.315	550.7[a]	0.571	--	0.00021
32	25	350	0.8	2.4	6.5	9	---	0.377	15.2	15.6	68.8	0.062
34	15	350	22	52	125	200	270	0.263	337.8	18.5	77.1	0.0027
35	9.5	350	145	390	1160[b]	---	---	0.104	432.8[a]	0.333	--	0.00042
37	7	500	0.4	1.0	2.6	4.5	7.1	0.115	14.6	50.4	85.5	0.17
38	5	500	1.7	5.0	12	25	43	0.037	124.6	40.0	73.1	0.037
310	3.5	500	5	25	80	160	320	0.030	1192.4	26.6	45.5	0.0036
311	1.5	500	60	425	2100[b]	---	---	0.070	748.8[a]	0.322	--	0.00018

(a) Test discontinued.
(b) Estimate.

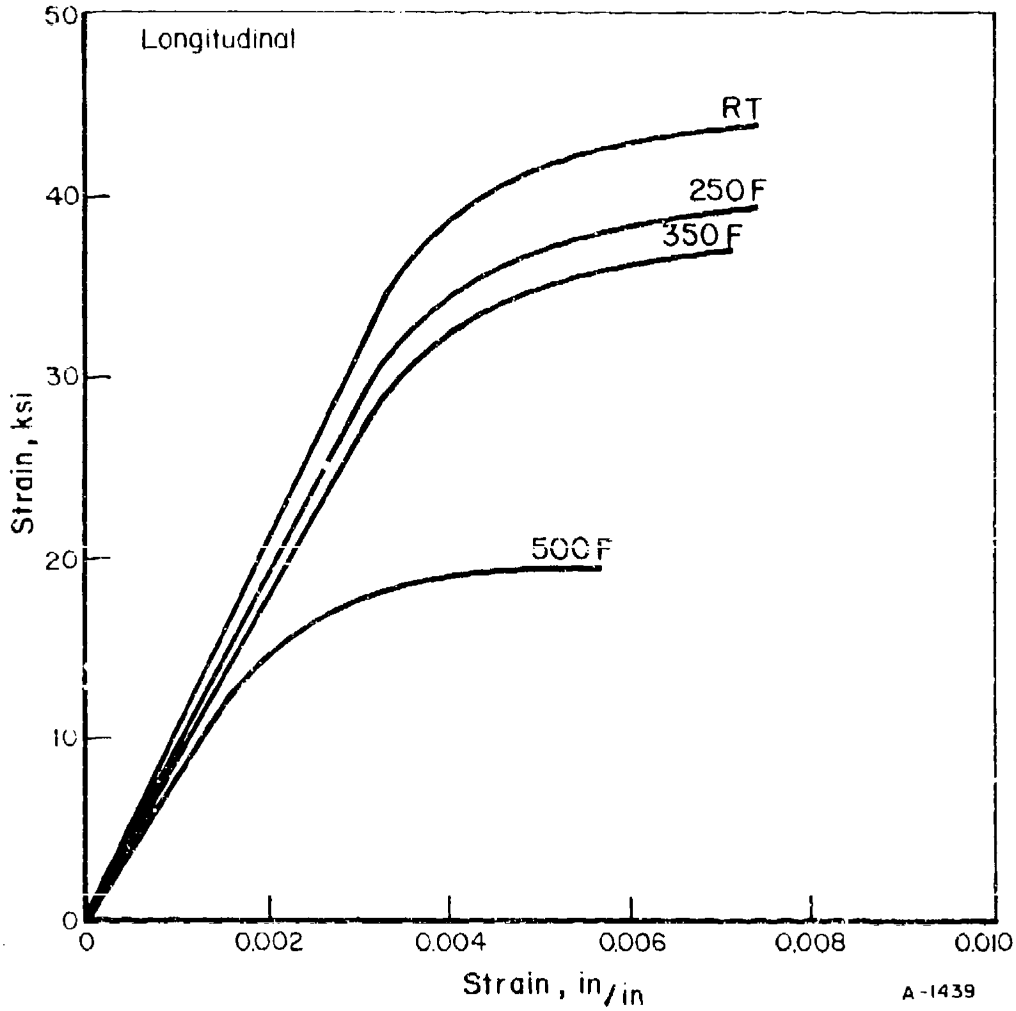

FIGURE 28. TYPICAL TENSILE STRESS-STRAIN CURVES FOR 2214-T351 PLATE (LONGITUDINAL)

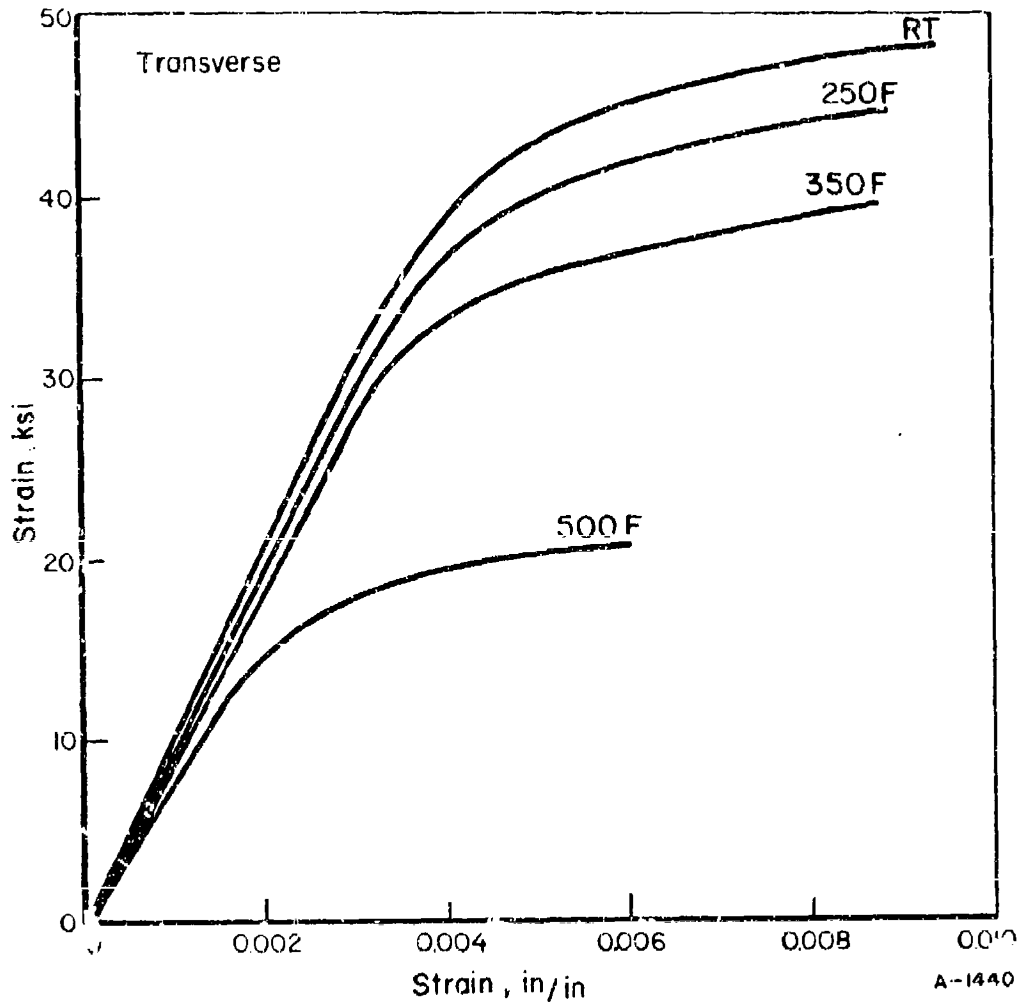

FIGURE 29. TYPICAL TENSILE STRESS-STRAIN CURVES FOR 2214-T351 PLATE (TRANSVERSE)

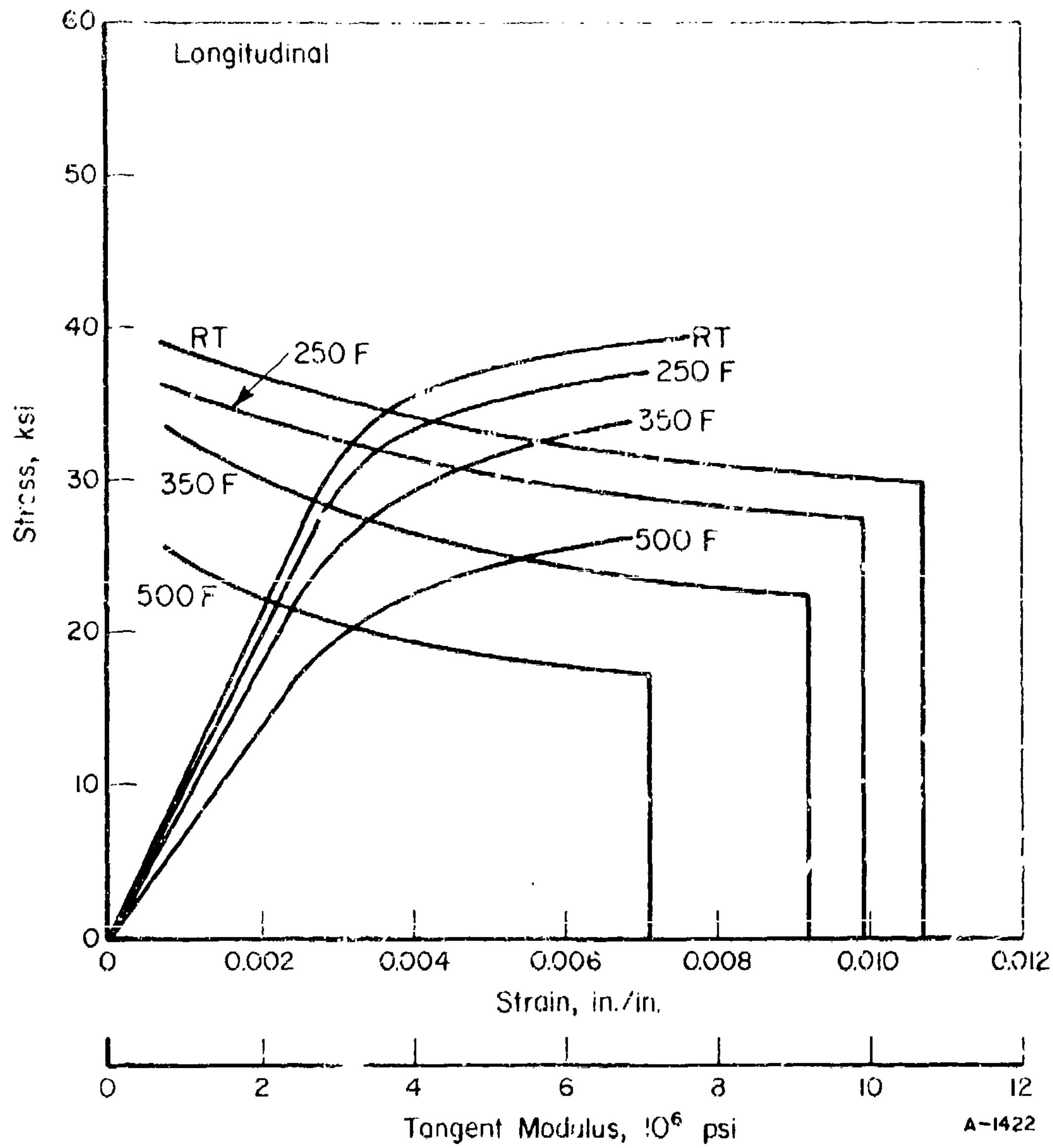

FIGURE 30. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT MODULUS CURVES FOR 2214-T351 PLATE (LONGITUDINAL)

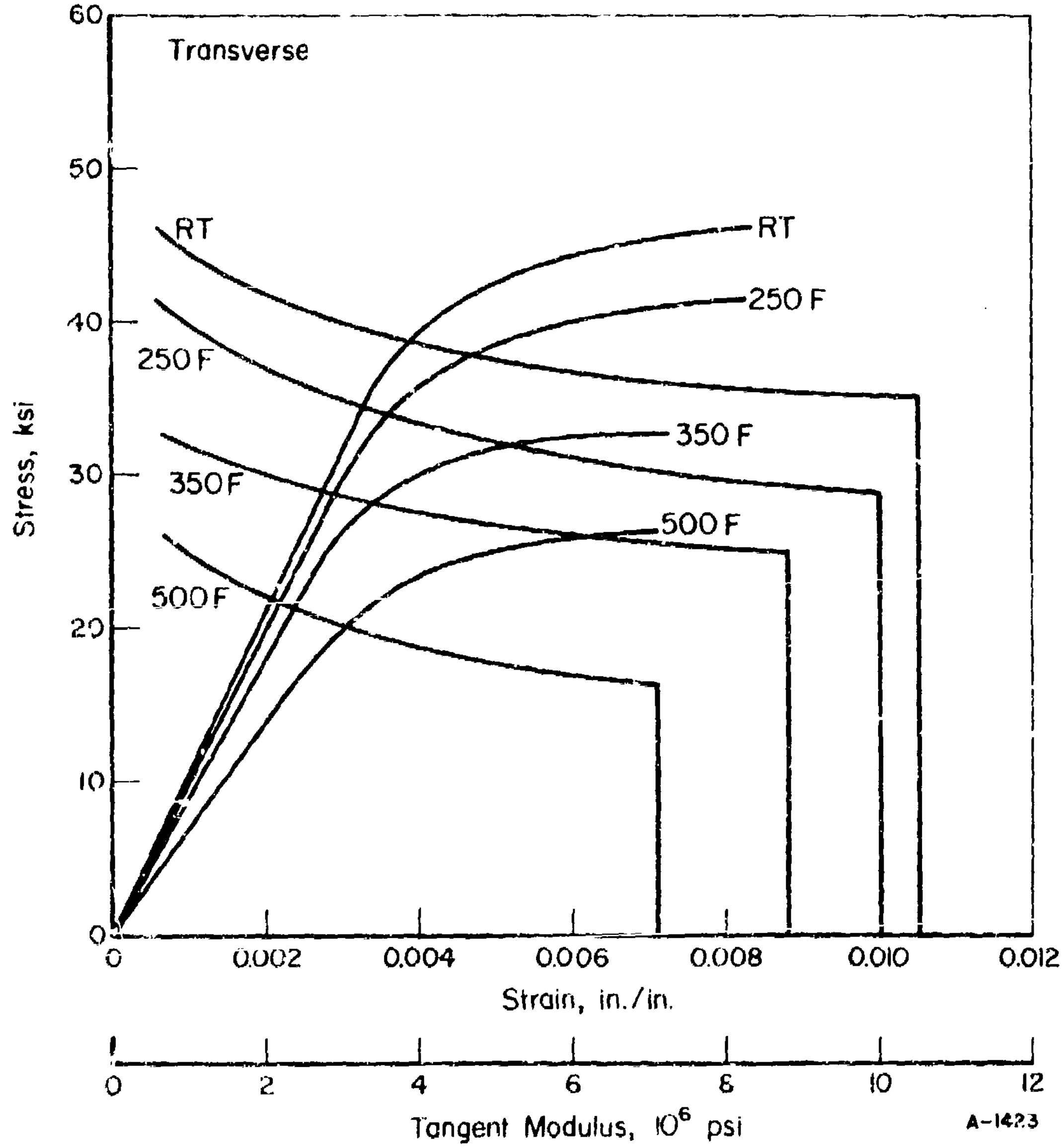

FIGURE 31. TYPICAL COMPRESSIVE STRESS-STRAIN AND TANGENT MODULUS CURVES FOR 2214-T351 PLATE (TRANSVERSE)

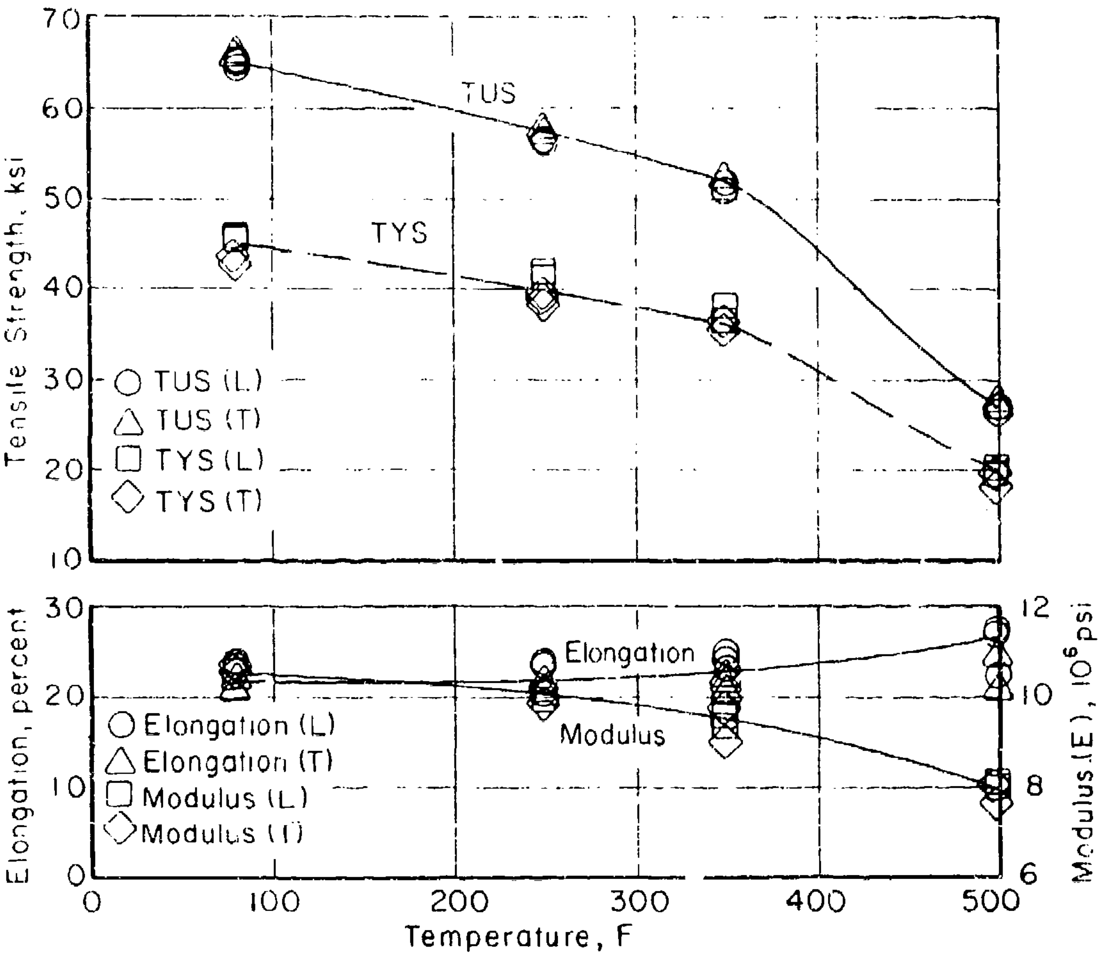

FIGURE 32. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF 2214-T351 PLATE

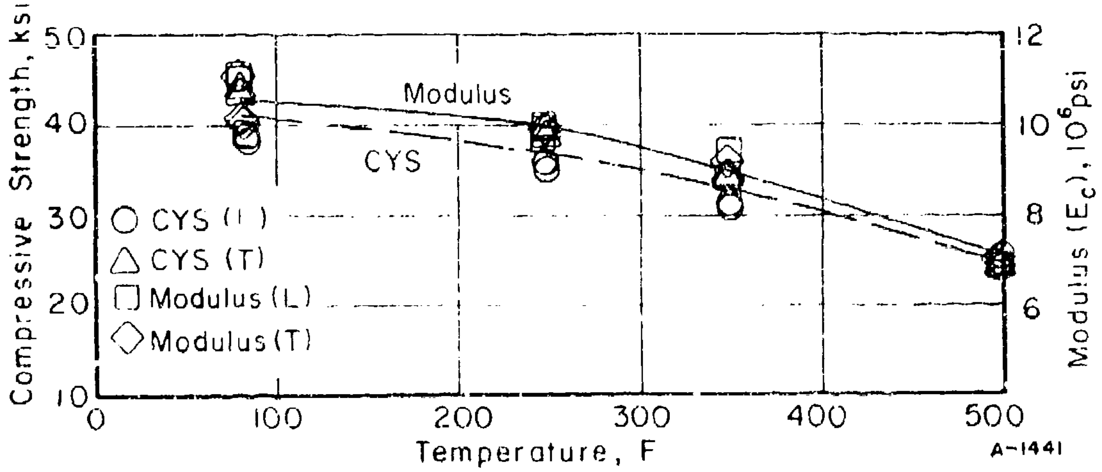

FIGURE 33. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF 2214-T351 PLATE

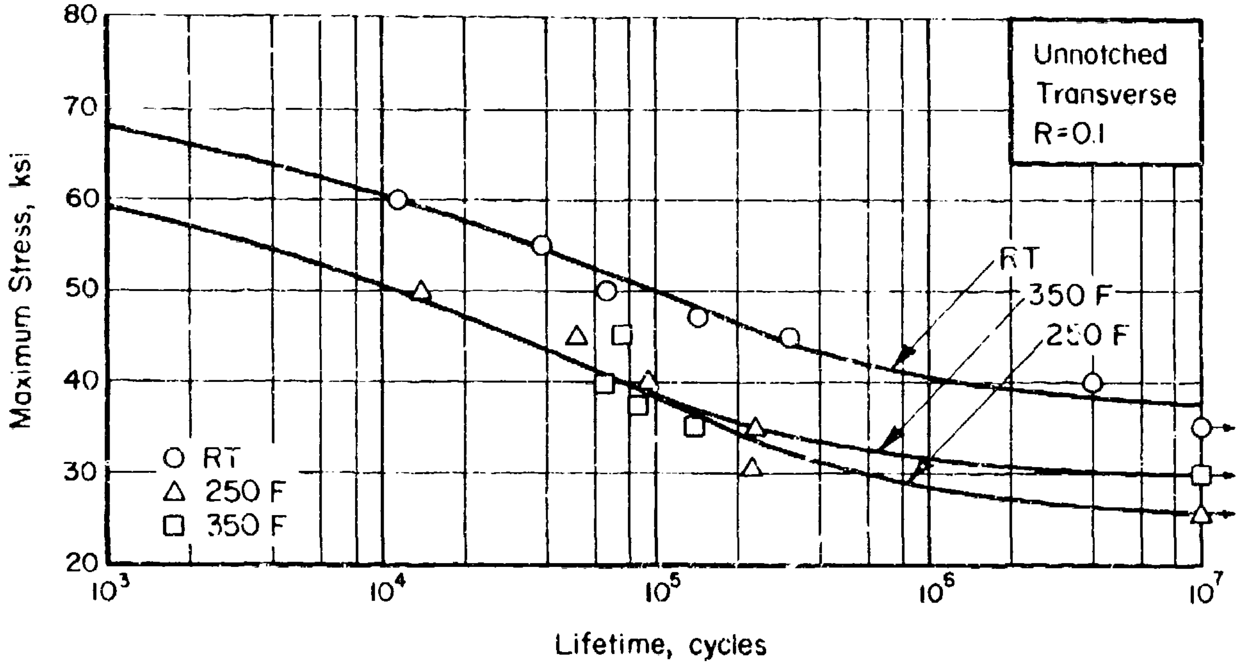

FIGURE 34. AXIAL-LOAD FATIGUE RESULTS FOR UNNOTCHED 2214-T351 PLATE

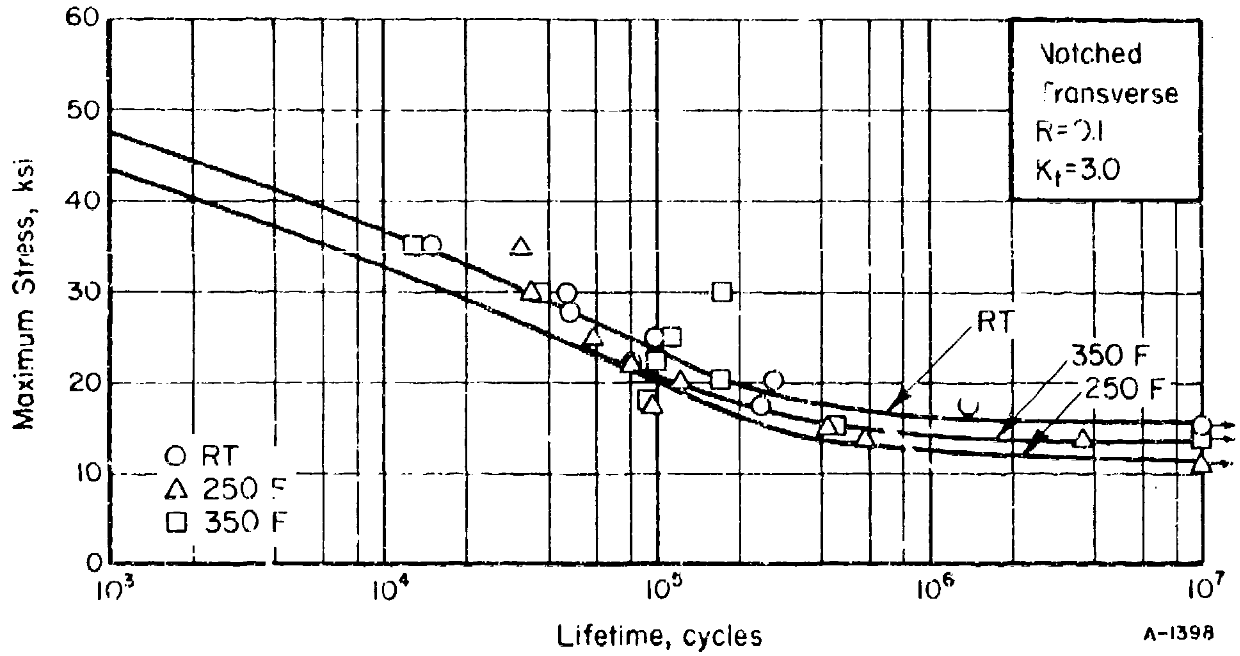

FIGURE 35. AXIAL LOAD FATIGUE RESULTS FOR NOTCHED (K_t = 3.0) 2214-T351 PLATE

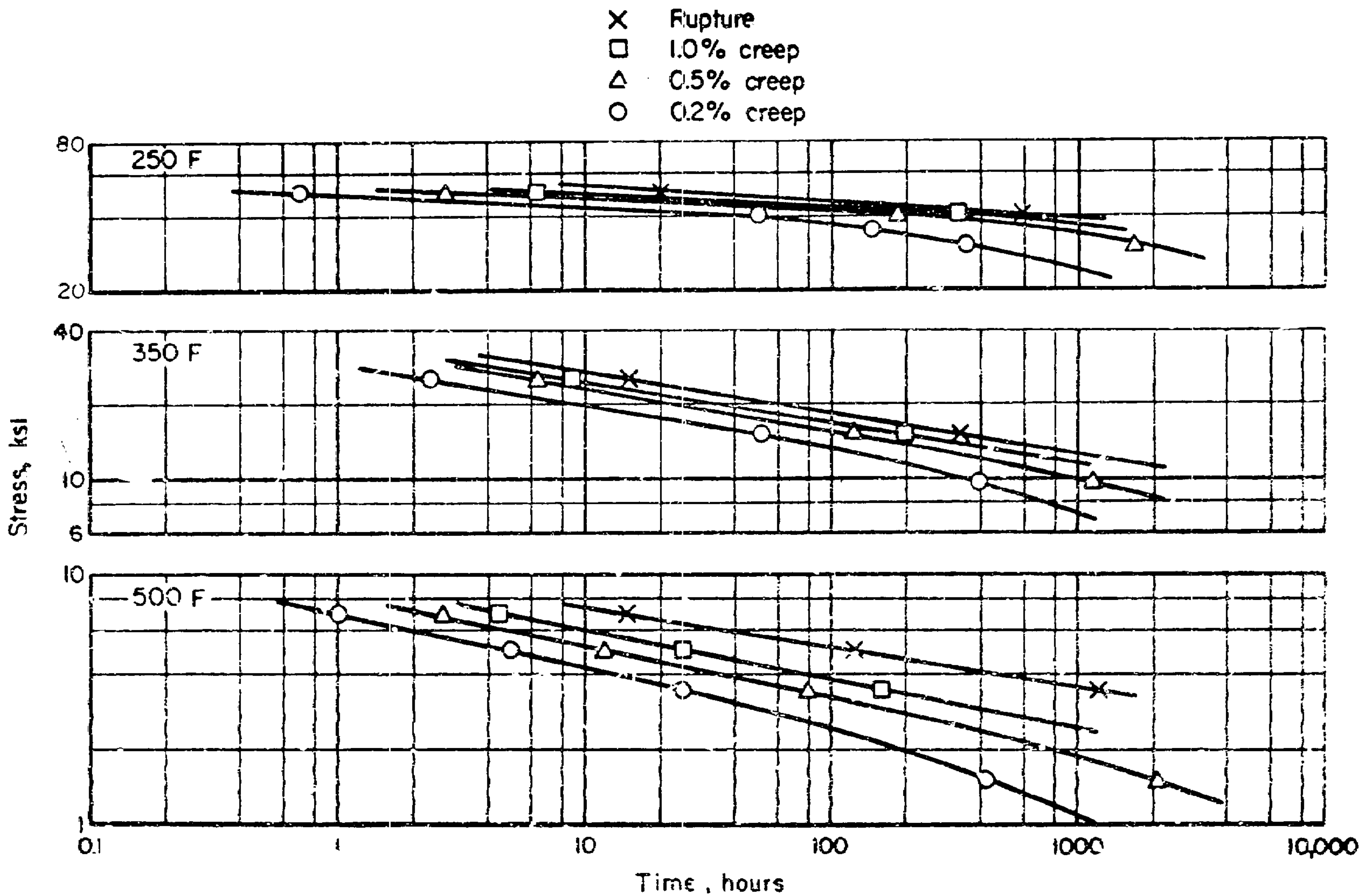

FIGURE 36. STRESS-RUPTURE AND ELASTIC DEFORMATION CURVES FOR 2214-T351 PLATE (TRANSVERSE)

Ti-6Al-4V Diffusion Bonded Component (DBHT)

Material Description

The material for this evaluation was supplied by the Air Force Materials Laboratory and consisted of pieces sectioned from a helicopter rotor hub. The rotor hub had been formed by diffusion bonding of 1/2-inch-thick Ti-6Al-4V plate. The evaluation material consisted of sections of the hub and lug ends.

Processing and Heat Treating

No specimen lay out is shown since the sections were quite complicated and it was necessary to cut specimens from wherever the section thickness allowed. Where possible, the bond line of the plates was perpendicular to the specimen axis. No heat treating was done since material was received in diffusion bonded heat treated (DBHT) condition.

Test Results

Tension. Test results for transverse specimens at room temperature, 400 F, 700 F, and 900 F are given in Table XXXIII. Stress-strain curves are shown in Figure 37. Effect of temperature curves are presented in Figure 39.

Compression. Test results for transverse specimens are given in Table XXXIV for room temperature, 400 F, 700 F, and 900 F. Stress-strain and tangent modulus curves are presented in Figure 38. Effect-of-temperature curves are shown in Figure 40.

Shear. Pin shear test results for longitudinal and transverse specimens at room temperature are given in Table XXXV.

Impact. Impact test results are given in Table XXXVI for longitudinal and transverse specimens.

Fracture Toughness. The material was not of sufficient size or quantity for these tests.

Fatigue. Axial-load test results for transverse specimens at room temperature, 400 F, and 700 F are given in Tables XXXVII and XXXVIII. S-N curves are presented in Figures 41 and 42.

Creep and Stress Rupture. Test results for longitudinal specimens are presented in Table XXXIX. Log-stress versus log-time curves are presented in Figure 43 for 500 F, 700 F, and 900 F.

Stress Corrosion. Tests were conducted as described in the experimental procedures section of this report. No failures or cracks occurred in the 1000-hour test duration.

Thermal Expansion. The coefficient of expansion for Ti-6Al-4V is 5.7×10^{-6} in./in./F for 68 F to 900 F.

Density. The density of this alloy is 0.160 lb/in.^{3}.

TABLE XXXIII. TENSILE TEST RESULTS FOR Ti-6Al-4V DIFFUSION BONDED COMPONENT (DBHT) (TRANSVERSE)

Specimen No.	Ultimate Tensile Strength, ksi	0.2 Percent Offset Yield Strength, ksi	Elongation in 2 Inches, percent	Tensile Modulus, 10^6 psi
		Room Temperature		
1T-1	153.0	143.0	11.5	15.8
1T-2	151.0	142.0	10.0	16.0
1T-3	150.0	145.0	12.0	16.0
		400 F		
1T-4	125.0	107.0	12.0	14.5
1T-5	124.0	112.0	11.5	14.8
1T-6	121.0	109.0	12.0	14.1
		700 F		
1T-7	106.0	90.2	8.5	13.0
1T-8	107.0	87.4	9.5	12.6
1T-9	108.0	88.5	8.5	12.0
		900 F		
1T-10	95.0	81.3	14.0	11.0
1T-11	93.2	79.9	18.5	11.1
1T-12	95.1	81.5	18.5	10.9

TABLE XXXIV. COMPRESSION TEST RESULTS FOR Ti-6Al-4V DIFFUSION BONDED COMPONENT (DBHT) (TRANSVERSE)

Specimen No.	0.2 Percent Offset Yield Strength, ksi	Compressive Modulus, 10^6 psi
	Room Temperature	
2T-1	144.0	17.7
2T-2	147.0	18.1
2T-3	148.0	17.9
	400 F	
2T-4	111.0	16.7
2T-5	111.0	16.6
2T-6	112.0	16.5
	700 F	
2T-7	99.1	14.7
2T-8	95.6	16.0
2T-9	96.5	15.7
	900 F	
2T-10	96.4	14.7
2T-11	87.0	14.3
2T-12	85.0	14.6

TABLE XXXV. SHEAR TEST RESULTS FOR Ti-6Al-4V DIFFUSION BONDED COMPONENT (DBHT)

Specimen No.	Ultimate Shear Strength, ksi
Longitudinal	
4L-1	91.0
4L-2	92.7
4L-3	93.7
Transverse	
4T-1	95.2
4T-2	91.2
4T-3	92.0

TABLE XXXVI. IMPACT TEST RESULTS FOR Ti-6Al-4V DBC (DBHT)

Specimen No.	Energy, ft-lb
Longitudinal	
10L-1	11.0
10L-2	13.0
10L-3	17.0
10L-4	16.0
Transverse	
10T-1	15.0
10T-2	16.0
10T-3	10.0
10T-4	12.0

TABLE XXXVII. AXIAL LOAD FATIGUE RESULTS FOR UNNOTCHED Ti-6Al-4V DBC (DBHT) (TRANSVERSE)

Specimen No.	Maximum Stress, ksi	Lifetime, cycles
	Room Temperature	
5-1	120.0	2,800
5-2	110.0	282,100
5-3	100.0	87,000
5-4	90.0	94,660
5-5	80.0	492,500
5-6	70.0	1,478,000
5-7	60.0	9,038,000
	400 F	
5-9	120.0	40
5-8	115.0	400
5-10	110.0	11,800
5-11	100.0	35,300
5-12	90.0	86,700
5-13	80.0	1,059,100
5-14	70.0	1,559,000
5-15	60.0	6,002,900
5-16	50.0	10,000,000 (a)
	700 F	
5-17	100.0	100
5-18	90.0	14,500
5-19	80.0	399,200
5-20	70.0	347,000
5-21	60.0	1,180,300
5-22	50.0	10,864,000 (a)

(a) Did not fail.

TABLE XXXVIII. AXIAL LOAD FATIGUE RESULTS FOR NOTCHED (K_t = 3.0) Ti-6Al-4V DBC (DBHT) (TRANSVERSE)

Specimen No.	Maximum Stress, ksi	Lifetime, cycles
	Room Temperature	
5-23	100.0	2,900
5-24	90.0	8,500
5-25	80.0	15,000
5-26	70.0	22,500
5-27	60.0	75,100
5-28	50.0	132,000
5-29	40.0	10,420,560[(a)]
	400 F	
5-30	100.0	2,400
5-31	90.0	3,800
5-32	80.0	8,700
5-33	70.0	11,800
5-34	60.0	18,500
5-35	50.0	55,900
5-36	40.0	250,600
5-37	30.0	12,609,000[(a)]
	700 F	
5-38	100.0	2,100
5-39	90.0	3,500
5-40	80.0	6,400
5-41	70.0	8,900
5-42	60.0	12,500
5-43	50.0	76,200
5-44	40.0	860,700
5-45	30.0	10,277,000[(a)]

(a) Did not fail.

TABLE XXXIX. SUMMARY CREEP AND RUPTURE DATA FOR Ti-6Al-4V DBC (DBHT) (LONGITUDINAL)

Specimen Number	Stress, ksi	Temperature, F	Hours to Indicated Creep Deformation, Percent 0.1	0.2	0.5	1.0	2.0	Initial Strain, percent	Rupture Time, hr.	Elongation in 2 Inches, percent	Minimum Creep Rate, percent/hr.
3		500	--	--	--	--	--	--	on loading	10.2	--
6	[illegible]	500	--	--	--	--	--	--	on loading	8.5	--
[illegible]	110	500	0.05	0.40	4000 est.	--	-	2.485	407.7*	2.772	0.00006
13	105	500	0.08	20	--	--	--	2.74[illegible]	26.7*	2.952	--
14	100	500	0.15	350	--	--	--	1.076	739.3*	1.286	0.00002
2	112	700	--	--	--	--	--	--	on loading	7.2	--
5	100	700	0.2	0.7	4.0	13	50	2.492	477.0	11.9	0.013
12	80	700	4.0	20	155	690	1850 est.	0.824	768.2*	1.896	0.00080
15	65	700	20	115	1000	3500 est.	--	0.543	840.6*	1.014	0.00020
1	95	900	--	--	--	--	--	--	0.1	11.9	--
4	80	900	--	0.01	0.05	0.15	0.35	1.353	2.3	19.1	5.1
8	60	900	0.07	0.2	0.8	2.5	5.7	0.676	60.8	35.7	0.27
11	50	900	0.15	0.4	2.7	7.0	20	0.402	194.6	45.5	0.085
9	35	900	0.50	1.7	7.0	20	50	0.266	71.7	[illegible].780	0.03
10	15	900	10	35	210	760	1900	0.083	863.1	[illegible].953	0.0009

*Test discontinued.

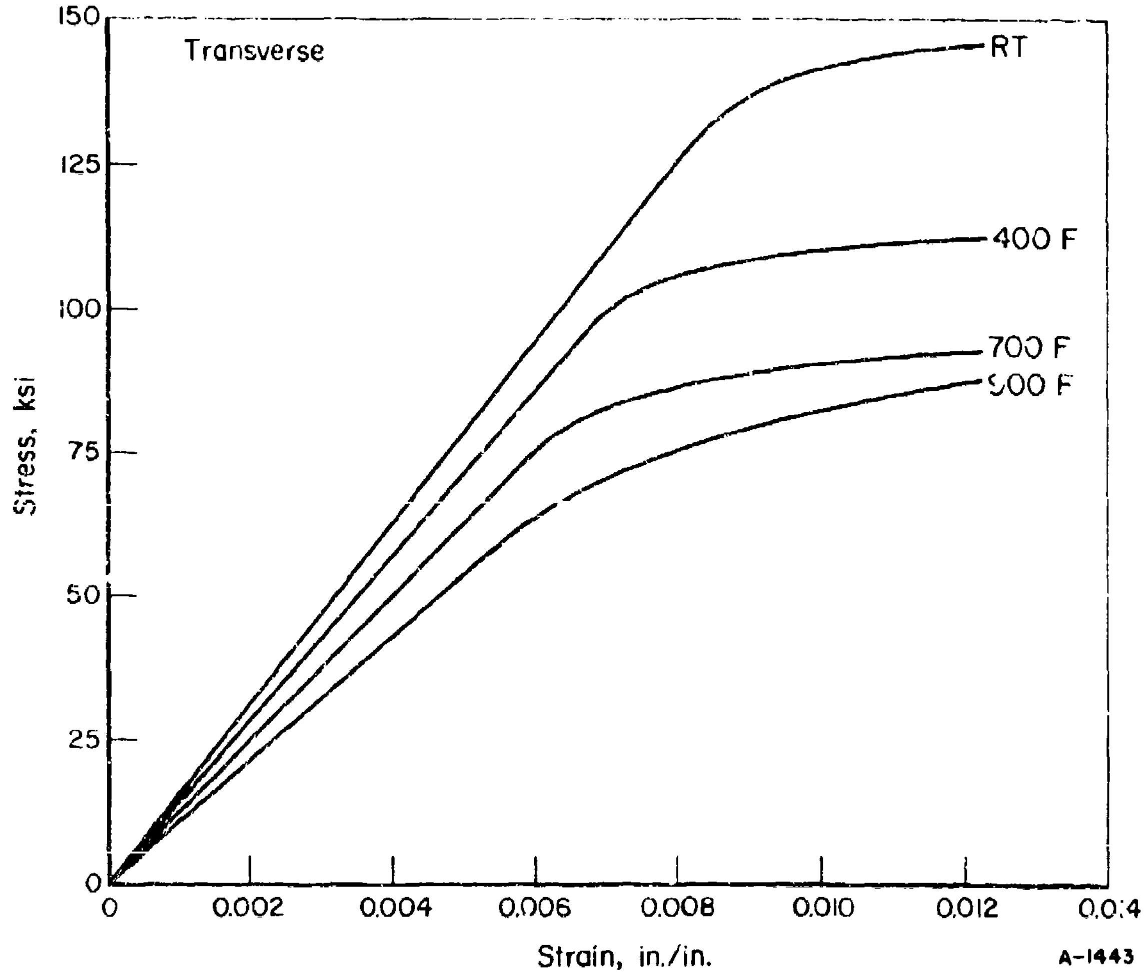

FIGURE 37. TYPICAL TENSILE STRESS-STRAIN CURVES FOR Ti-6Al-4V DBC (DBHT) (TRANSVERSE)

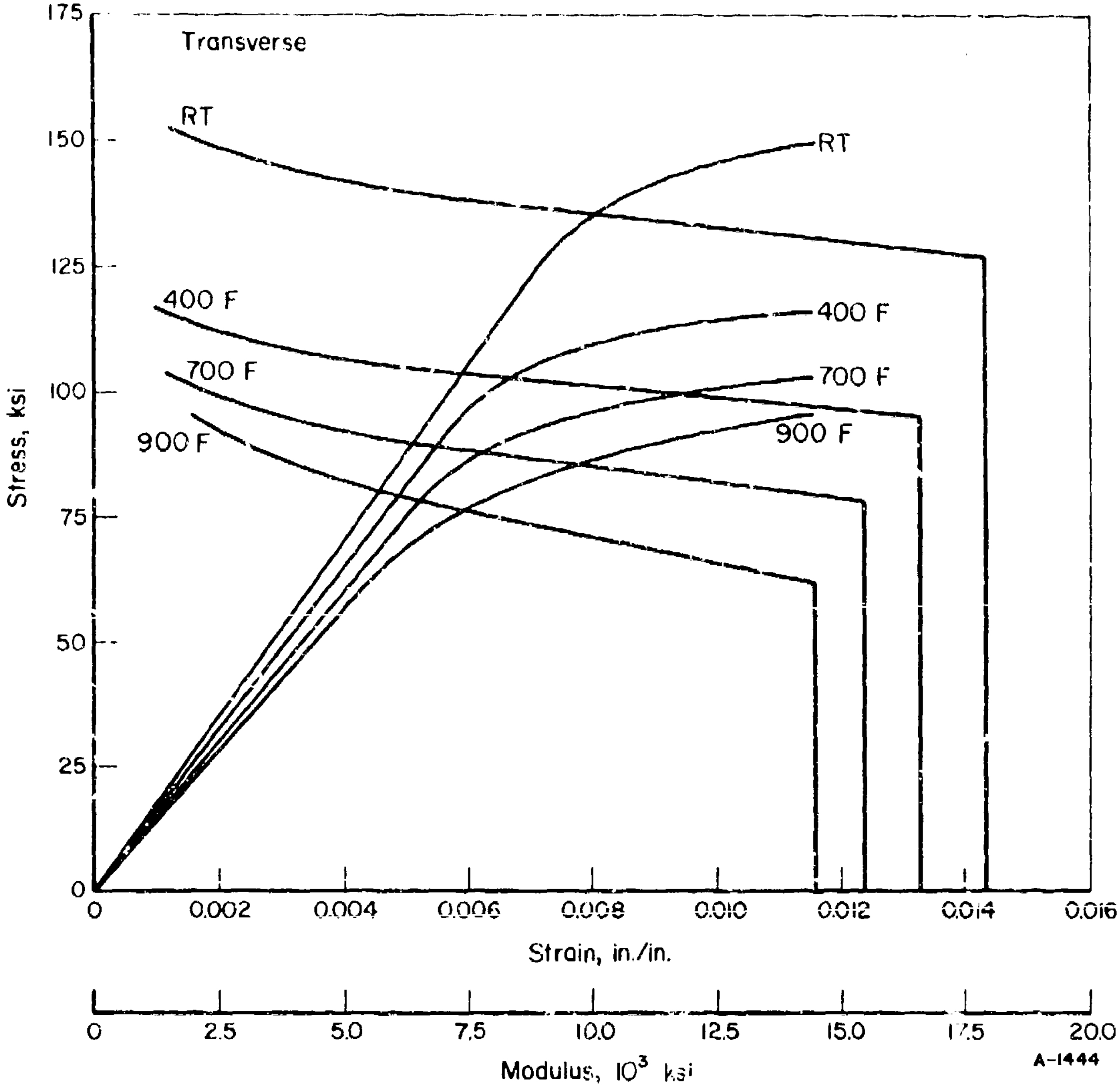

FIGURE 38. TYPICAL COMPRESSION STRESS-STRAIN AND TANGENT MODULUS CURVES FOR Ti-6Al-4V DEC (DBHT) (TRANSVERSE)

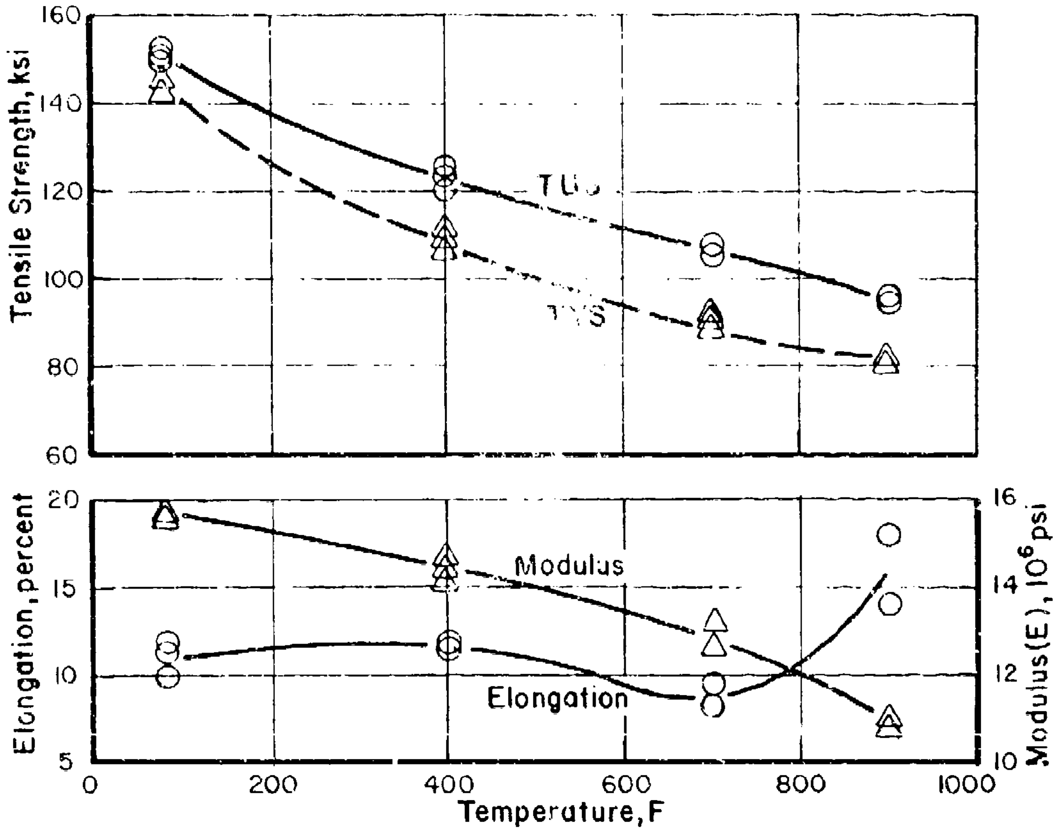

FIGURE 39. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF Ti-6Al-4V DBC (DBHT)

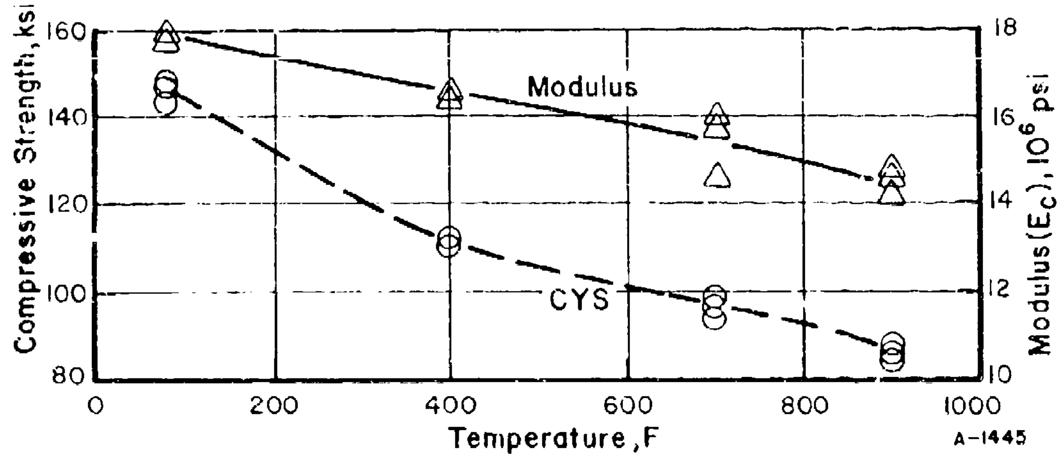

FIGURE 40. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF Ti-6Al-4V DBC (DBHT)

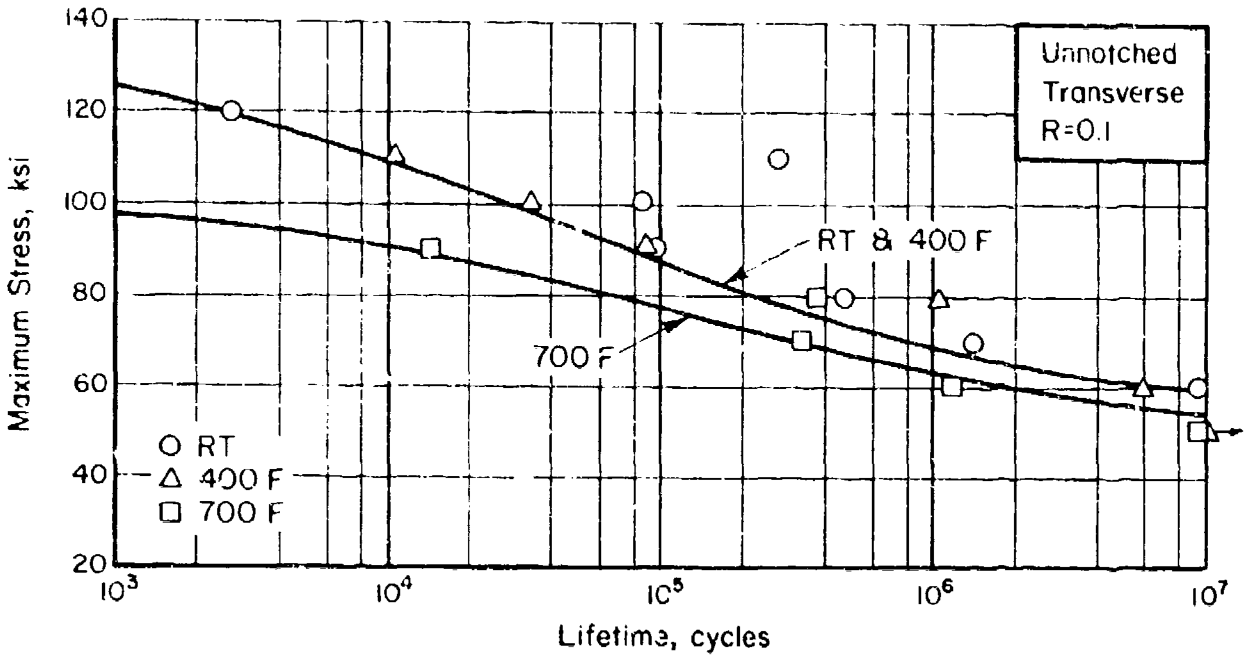

FIGURE 41. AXIAL LOAD FATIGUE RESULTS FOR UNNOTCHED Ti-6Al-4V DBC (DBHT)

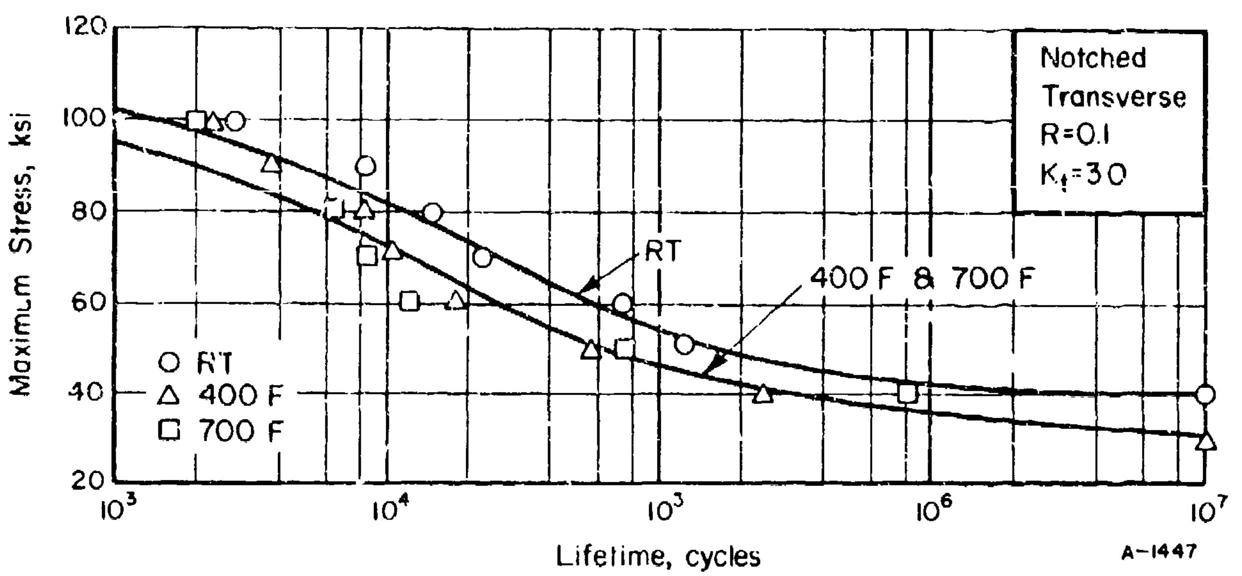

FIGURE 42. AXIAL-LOAD FATIGUE RESULTS FOR NOTCHED (K_t = 3.0) Ti-6Al-4V DBC (DBHT)

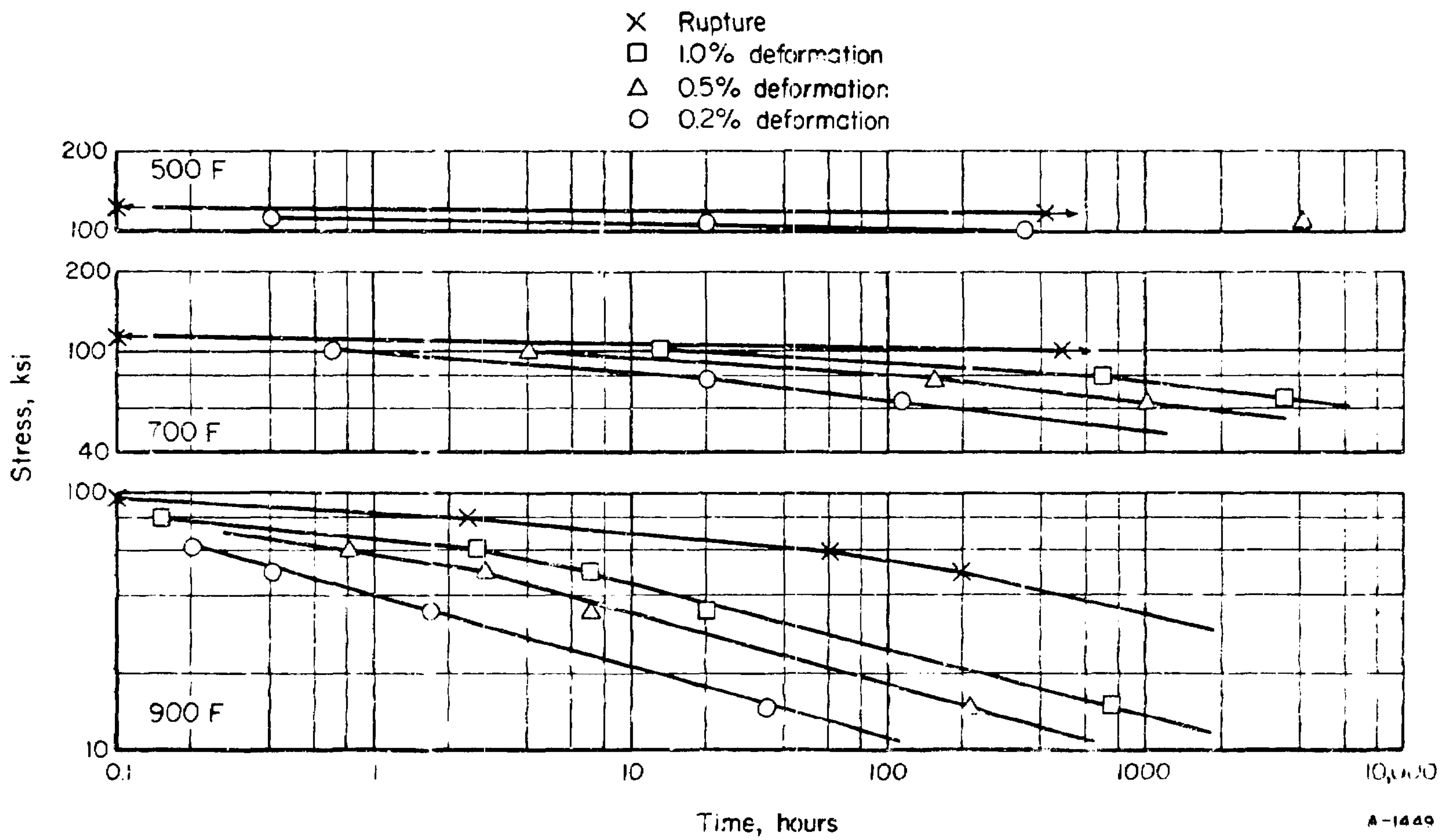

FIGURE 43. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR Ti-6Al-4V DBC (DBHT) (LONGITUDINAL)

DISCUSSION OF PROGRAM RESULTS

The tendency in an evaluation program of this type is to compare the materials property information obtained with similar data on materials already in use. Whether such a comparison should be the deciding factor for interest in a newer alloy is open to question. Many criteria such as forming characteristics, weldability, oxidation resistance, etc., can be of particular importance so that strength properties may become secondary. However, since first comparisons are usually made on the basis of mechanical strength (tensile ultimate and tensile yield) the data generated on this program are compared to information for similar alloys. Figures 44 and 45 are effect of temperature curves concerned with these properties.

CONCLUSIONS

The objective of this program was the generation of useful engineering data for newly developed materials. During the contract term the following materials were evaluated:

(1) 17-4 PH (H900) ESR Bar

(2) Udimet 710 Forged Bar

(3) X7050-T7E56 Hand Forging

(4) 2214-T351 (Alcoa 417 Process) Plate

(5) Ti-6Al-4V (DBHT) Diffusion Bonded Component.

A data sheet was issued for each material. As a summary, each of the data sheets is reproduced in Appendix III.

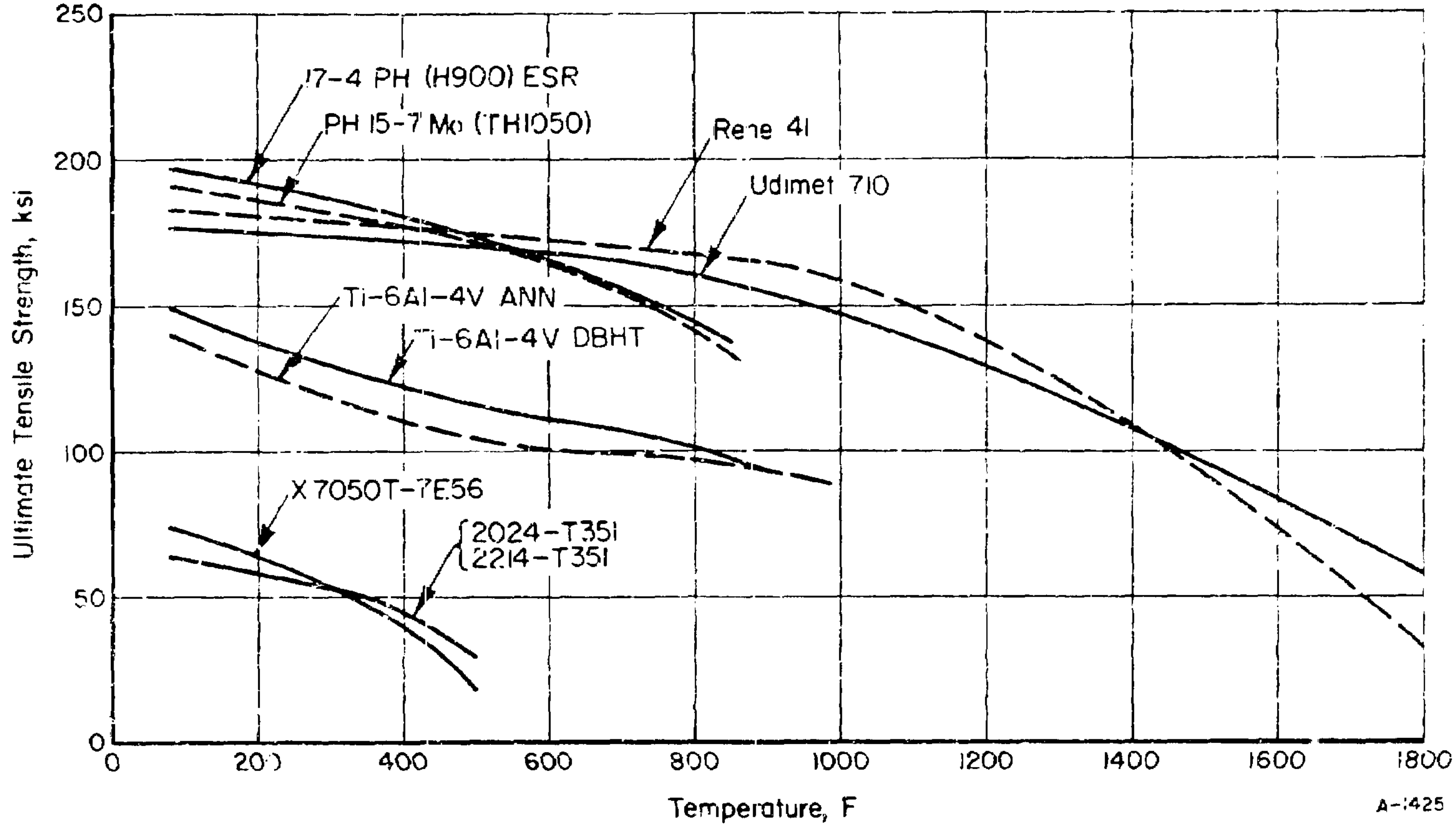

FIGURE 44. TENSILE ULTIMATE STRENGTH AS A FUNCTION OF TEMPERATURE

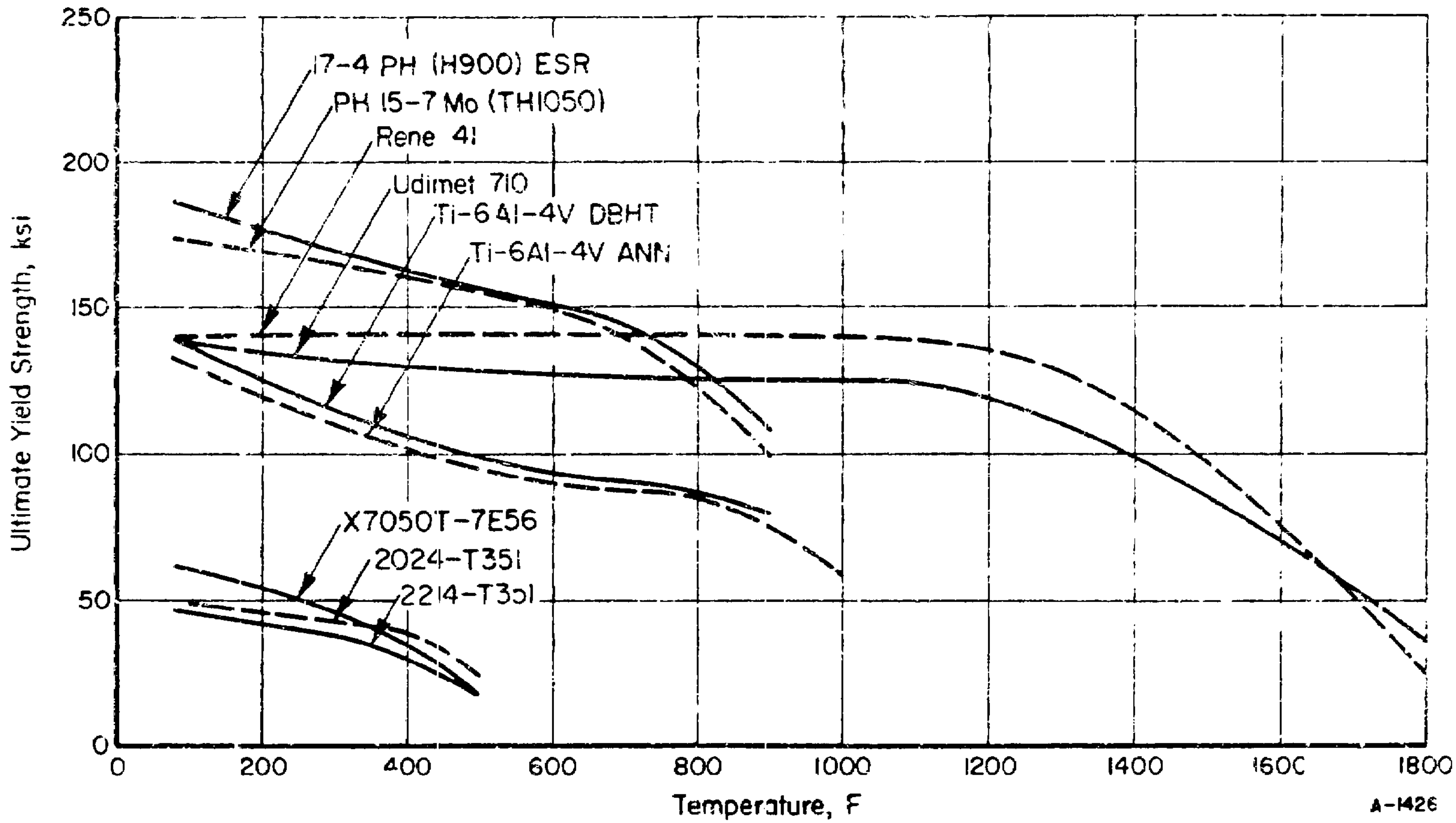

FIGURE 45. TENSILE YIELD STRENGTH AS A FUNCTION OF TEMPERATURE

APPENDIX I

EXPERIMENTAL PROCEDURE

APPENDIX I

EXPERIMENTAL PROCEDURE

Mechanical Properties

The various mechanical properties of interest for each of the materials are as follows:

(1) Tension

(a) Tensile ultimate strength, TUS

(b) Tensile yield strength, TYS

(c) Elongation, e_t

(d) Reduction in area, RA

(e) Modulus of elasticity, E_t.

(2) Compression

(a) Compressive yield strength, CYS

(b) Modulus of elasticity, E_c.

(3) Creep and stress-rupture

(a) Stress for 0.2 or 0.5 percent deformation in 100 hours and 1000 hours

(b) Stress for rupture in 100 hours and 1000 hours.

(4) Shear

(a) Shear ultimate strength, SUS

(5) Axial fatigue*

(a) Unnotched, R = 0.1, lifetime: 10^3 through 10^7 cycles

* "R" represents the algebraic ratio of the minimum stress to the maximum stress in one cycle; that is, $R = S_{min}/S_{max}$. "K_t" represents the Neuber-Peterson theoretical stress concentration factor.

(b) Notched (K_t = 3.0), R = 0.1, lifetime: 10^3 through 10^7 cycles.

(6) Fracture toughness, K_{Ic} or K_c

(7) Stress corrosion

(a) 80 percent TYS for 1000 hours maximum, 3-1/2 percent NaCl solution.

(8) Thermal expansion.

(9) Bend

(a) Minimum radius.

(10) Impact

(a) Charpy V-notch.

(11) Density.

Specimen Identification

A simple system of numbers and letters was used for specimen identification. Coding consisted of a number indicating the type of test and also indicating a comparable area on the sheet, plate, or forging. For certain test types, the number was followed by a letter signifying specimen orientation (L for longitudinal, T for transverse, ST for short transverse). The test types where the letter did not appear were creep, fatigue, and bend since, in these cases, only one specimen orientation was used. The next number in the coding specifies the location from which the specimen blank was taken from the original material configuration. Coding was as follows:

Assigned Number	Test Type
1	Tension
2	Compression
3	Creep and stress-rupture
4	Shear
5	Fatigue
6	Fracture toughness

Assigned Number	Test Type
7	Stress corrosion
8	Thermal expansion
9	Bend
10	Impact
11	Density

As an example, a specimen numbered 2-T5 is a compression specimen, transverse orientation, cut from Location 5. Also, a specimen numbered 5-12 is a fatigue specimen cut from Location 12.

Test Description

Tension

Procedures used for tension testing are those recommended in ASTM methods E8-68 and E21-66T as well as in Federal Test Method standard No. 151a (method 211.1). Six specimens (three longitudinal and three transverse) were tested at each temperature to determine ultimate tensile strength, 0.2 percent offset yield strength, elongation, and reduction in area. The modulus of elasticity was obtained from load-strain curves plotted by an autographic recorder during each test.

All tensile tests were carried out in Baldwin Universal testing machines. These machines are calibrated at frequent intervals in accordance with ASTM method E4-64 to assure loading accuracy within 0.2 percent. The machines are equipped with integral automatic strain pacers and autographic strain recorders.

Specimens tested at elevated temperatures were heated in standard wire-wound resistance-type furnaces. Each furnace was equipped with a Foxboro controller capable of maintaining the test temperature to within 5 F of the control temperature over a 2-inch gage length. Chromel-Alumel thermocouples attached to the specimen gage section were used to monitor temperatures. Each specimen was soaked at temperature at least 20 minutes before being tested.

An averaging-type linear differential transformer extensometer was used to measure strain. For elevated temperature testing, the extensometer was equipped with extensions to bring the transformer unit out of the furnace. The extensometer conformed to ASTM E3-64T Classification B1 having a sensitivity of 0.0001 inch/inch. The strain rate in the elastic region was maintained at 0.005 inch/inch/minute. After yielding occurred, the head speed was increased to 0.1 inch/inch/minute until fracture.

Compression

Procedures for conducting compression tests are outlined in ASTM Method E9-67 along with temperature control provisions of E21-66T. All sheet and thin plate tests were carried out in Baldwin Universal testing machines using a North American type compression fixture as shown in Reference 2. Specimen heating was accomplished by a forced-air furnace for temperatures up to 1000 F. Specimen temperature was maintained by means of a Wheelco pyrometer. Three Chromel-Alumel thermocouples attached to the fixture were used to monitor temperatures to within 3 F of the test temperature. For higher temperatures, wire-wound furnaces were used with controls as described in the tensile test section.

The extensometer used for the compression tests was quite similar to that used in the tensile testing. The extension arms were fastened to the specimen at small notches spanning a 2-inch gage length. The output from the microformer was fed into a load-strain recorder to provide autographic load-strain curves. During testing the strain rate was adjusted to 0.005 inch/inch/minute.

For bar and forging material, cylindrical specimens similar to those described in ASTM E9-67 were used with appropriate temperature control and strain measurement as described above.

Six specimens (three longitudinal and three transverse) were tested at each temperature.

Shear

Single-shear sheet-type specimens were used for sheet and thin-plate material; for bar and forgings, a double-shear pin-type was used. Shear testing was performed at room temperature only. A minimum of six specimens (three longitudinal and three transverse) were used to determine ultimate shear strength.

Bend

The procedures for conducting bend tests are described in Report MAB-192-M. The specimens were placed in a rigid three-point loading fixture and bending tups of various sizes were used to determine the minimum bend radius at room temperature.

Creep and Stress Rupture

Standard dead-weight type creep testing frames were used for the creep and stress-rupture tests. These machines are calibrated to operate well within the accuracy requirements of ASTM method E139-66T.

Specimens similar to those used for tension tests were used for the creep and stress-rupture studies. A platinum strip "slide rule" extensometer is attached for measuring creep strain and three Chromel-Alumel thermocouples are attached to the gage section for temperature measurements. Extensometer measurements were made visually through windows in the furnace by means of a filar micrometer microscope in which the smallest division equals 0.00005 inch.

The furnace was of conventional Chromel A wire-wound design with taps along the side to allow for correcting small temperature differences. Furnace temperature was maintained to within $\pm$ 2 F by Foxboro controllers in response to signals from the centrally located thermocouple. The temperature of a specimen under test was stabilized for at least 1/2 hour prior to loading.

For each temperature condition creep and stress-rupture data were obtained to 100 and 1000 hours using as many specimens as necessary to obtain precise information. The percent creep deformation obtained was dependent on the material under test. In most instances stress-time curves were defined for 0.2 and 0.5 percent elongation.

Stress Corrosion

Seven specimens of each alloy were tested for susceptibility to stress-corrosion cracking by alternate immersion in 3-1/2 percent sodium chloride solution at room temperature.

Specimens were prepared for testing by degreasing with acetone. Where a surface film remained from heat treating, it was abraded off one side and the adjacent long edge of five of the specimens, and left intact on the other two.

Each specimen was placed in a four-point loading fixture and deflected to a stress corresponding to 80 percent of the tensile yield strength of the particular material. The specimen was electrically insulated from the fixture by means of glass or sapphire rods. Deflection for a given maximum fiber stress was calculated by the following expression:

$$y = \frac{\sigma(3\ell^2-4a^2}{12dE}$$

where

y = deflection

σ = maximum fiber stress

ℓ = distance between outer load points

a = distance between outer and inner load points

d = specimen thickness

E = modulus of specimen material.

Each stressed specimen was suspended on an alternate immersion unit. This unit alternately immersed specimens in the 3.5 percent sodium chloride solution for ten minutes and held them above the solution to dry for 50 minutes. Tests were continued to the first sign of cracking or for 1000 hours, whichever occurred first.

Specimens were given frequent low-power microscopic examinations to detect cracks. At the first sign of cracking the specimen was removed. At the conclusion of the test, selected samples were sectioned and examined metallographically for any indication of cracking. Representative samples in which cracks were found were also given a metallographic examination to establish the type and extent of the cracks.

Thermal Expansion

Linear-thermal-expansion measurements were performed in a recording dilatometer with specimens protected by a vacuum of about 2×10^{-6} mm of mercury. In this apparatus a sheet-type specimen is supported between two graphite structures inside a tantalum-tube heater element. On heating, the differential movement of the two structures caused by specimen expansion results in the displacement of the core of a linear-variable differential transformer. The output of the transformer is recorded continuously as a function of specimen temperature. The entire assembly is enclosed in a vacuum chamber.

The furnace is controlled to heat at the desired rate, usually 5 F per minute. Errors associated with measurements in this apparatus are estimated not to exceed $\pm$ 2 percent. This is based on calibration with materials of known thermal-expansion characteristics.

Fatigue

Fatigue tests were conducted using MTS electrohydraulic-servocontrolled testing machines. The frequency of cycling of these machines is variable to beyond 2,000 cpm depending on specimen rigidity. These machines operate with closed-loop deflection, strain or load control. Under load control used in this program, cyclic loads were automatically maintained (regardless of the required amount of ram travel) by means of load-cell feedback signals. The calibration and alignment of each machine are checked periodically. In each case, the dynamic load-control accuracy is better than $\pm$ 3 percent of the test load.

For elevated temperature studies, an induction heating coil controlled by a Lepel Induction Heater was used. A thermocouple placed on the center of the specimen controlled temperature to $\pm$ 5 degrees.

After machining and heat treating (when required), the edges of all sheet and plate specimens were polished according to Battelle-Columbus' standard practice prior to testing. The unnotched specimens were held against a rotating drum covered with emery paper and polished using a kerosene lubricant. Successively finer grits of emery paper were used, as required, to produce a surface

of about 10 RMS. Unnotched round specimens were polished in the Battelle-Columbus polishing apparatus. This machine utilizes a rotating belt sander driven rectilinearly along the specimen test section while the specimen is being rotated. The belt speed and specimen speed are adjusted so that polishing marks on the specimen are in the longitudinal direction. The surface finish is about the same as that on the flat specimens. The notched flat specimens were held in a fixture and polished with a slurry of oil and alundum grit applied liberally to a rotating wire. Notched round specimens are polished in the same manner, except that the specimen is rotated.

A shadowgraph optical comparator was used for measuring the test sections of all polished specimens and for inspection of the root radius in the case of the notched specimens.

The stress ratio for all specimens was R = 0.1. Stresses for notched (K_t = 3.0) and unnotched specimens were selected so that S-N curves were defined between 10^3 and 10^7 cycles using approximately 10 specimens for each set of fatigue conditions.

Fracture Toughness

Two types of fracture toughness tests were used. For heavy section materials, the chevron-notched, slow bend test specimen of ASTM Method E-399-72 was selected. For thinner section sheet materials, center through-cracked tension panels were used as test specimens. All specimens were precracked in fatigue and subsequently fractured in a servocontrolled electrohydraulic testing system of appropriate load capacity.

The slow-bend type specimens were precracked and tested under 3-point loading. The pop-in load for materials susceptible to brittle fracture was determined from the load-compliance curve. When pop-in was not detectable, the curves were analyzed using the 5 percent secant offset method of the ASTM procedure.

The thin sheet center through-crack tension panels were initially saw-cut and then precracked in constant amplitude fatigue loading. In order to maintain a flat fatigue crack and not plastically strain the uncracked section, the maximum stresses were adjusted to keep the applied stress-intensity factor less than one-third or one-quarter of that anticipated at fracture. This usually involved stepping down the stresses as the cracking proceeded. The crack was extended to approximately one-quarter of the panel width. Buckling guides were attached and a clip-type compliance gage was mounted in the central notch. The panels were fractured in a rising load test at a stress rate in the range

$$.002\ E < \dot{S} < .005\ E\ \text{ksi/min} \quad ,$$

which corresponds nominally to the gross strain rate of standard tensile testing.

APPENDIX II

SPECIMEN DRAWINGS

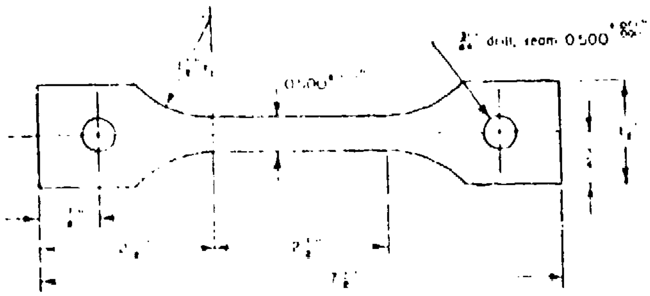

FIGURE 46. SHEET AND THIN-PLATE TENSILE SPECIMEN

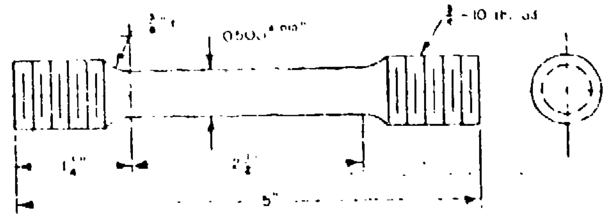

FIGURE 47. ROUND TENSILE SPECIMEN

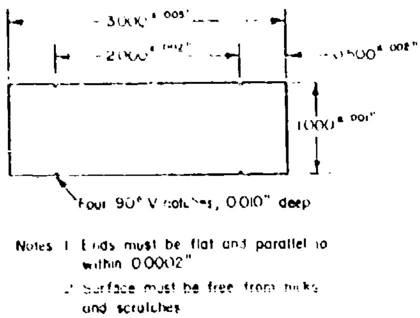

FIGURE 48. SHEET COMPRESSION SPECIMEN

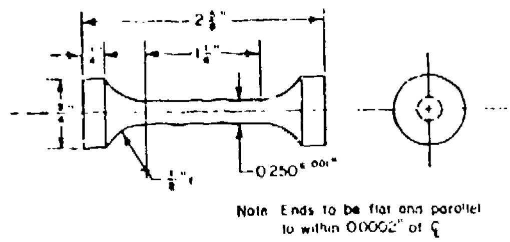

FIGURE 49. ROUND COMPRESSION SPECIMEN

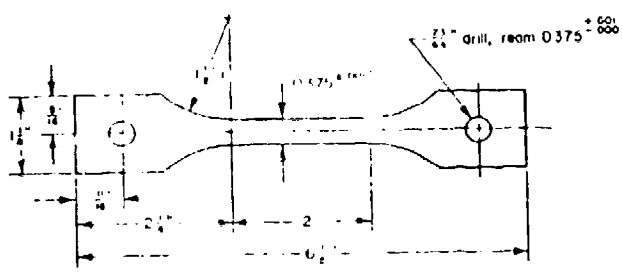

FIGURE 50. SHEET CREEP - AND STRESS-RUPTURE SPECIMEN

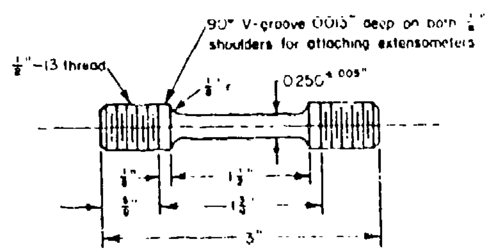

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FIGURE 51. ROUND CREEP - AND STRESS-RUPTURE SPECIMEN

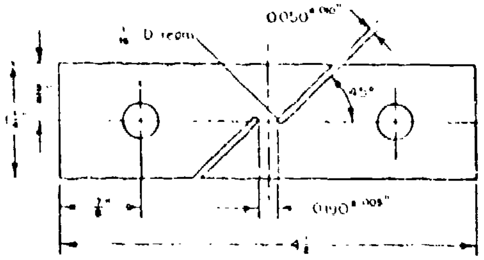

FIGURE 52. SHEET SHEAR TEST SPECIMEN

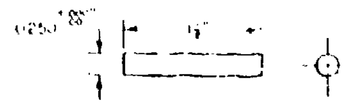

FIGURE 53. PIN SHEAR SPECIMEN

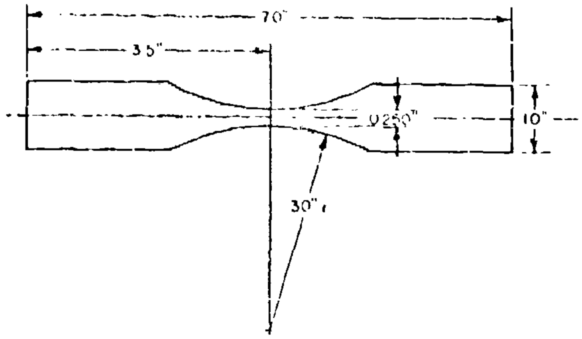

FIGURE 54. UNNOTCHED SHEET FATIGUE SPECIMEN

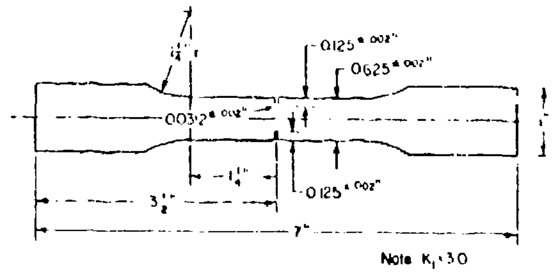

FIGURE 55. NOTCHED SHEET FATIGUE SPECIMEN

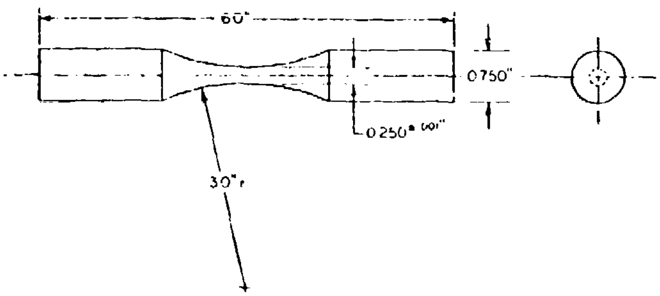

FIGURE 56. UNNOTCHED ROUND FATIGUE SPECIMEN

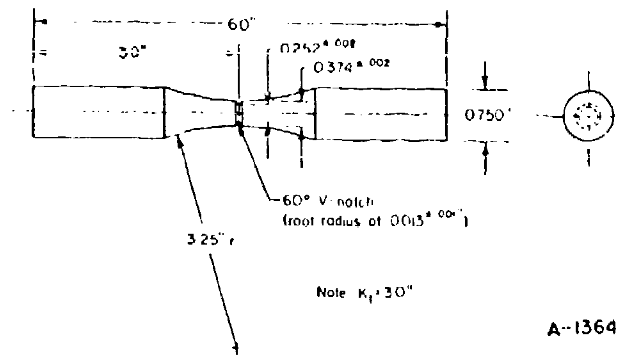

FIGURE 57. NOTCHED ROUND FATIGUE SPECIMEN

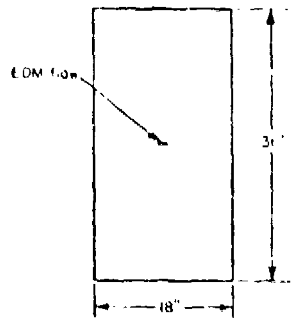

FIGURE 58. SHEET FRACTURE TOUGHNESS SPECIMEN

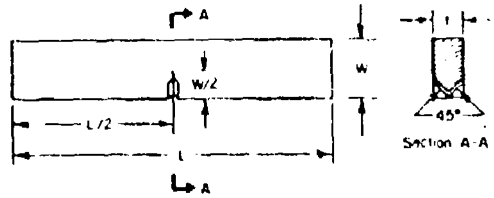

FIGURE 59. SLOW BEND FRACTURE TOUGHNESS SPECIMEN

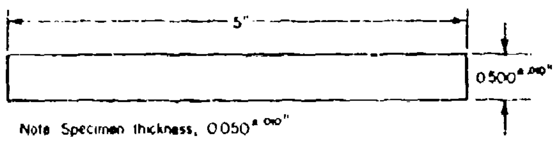

FIGURE 60. STRESS-CORROSION SPECIMEN

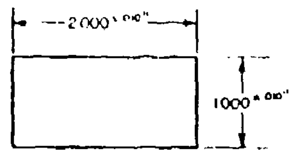

FIGURE 61. THERMAL-EXPANSION SPECIMEN

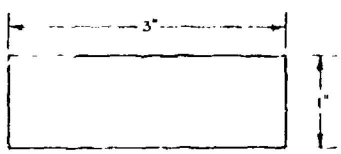

FIGURE 62. SHEET BEND SPECIMEN

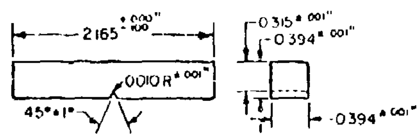

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FIGURE 63. NOTCHED IMPACT SPECIMEN

APPENDIX 111

DATA SHEETS

17-4 PH (H900) Bar (ESR)

Material Description

This alloy is one of the family of precipitation hardening stainless steels which have found wide usage in aerospace, industrial, and commercial applications. The particular material used in this evaluation was produced by the Electroslag Remelting (ESR) process. In this process an electrode (in this case, air melted 17-4 PH) is melted in a resistance heated molten bath of flux contained in an open-bottomed water-cooled metal mold. The melted metal forms a pool beneath the flux bath and progressively solidifies forming an ingot which is continuously extracted from the mold.

The metal is refined and desulfurized by flux action and the microstructure is improved by controlled solidification.

The material used in this evaluation was a 3.3-inch-diameter bar from Heat 02298. Chemistry was as follows:

Chemical Composition	Percent
Carbon	0.04
Manganese	0.70
Silicon	0.41
Phosphorus	0.15
Sulfur	0.08
Chromium	15.9
Nickel	4.45
Copper	3.45
Columbium	0.23
Iron	Balance

Processing and Heat Treating

Specimens were machined in the as-received Condition A followed by heat treatment at 900 F for 1 hour to Condition H 900.

17-4 PH ESR Data(a)

Condition: H900
Product: 3.3-inch diameter bar

Properties	Temperature, F RT	400	700	900
Tension				
TUS (longitudinal), ksi	197.2	177.5	160.4	139.4
TYS (longitudinal), ksi	165.6	159.3	145.0	108.2
e (longitudinal), percent in 2 in.	17.1	10.9	9.9	9.7
RA (longitudinal), percent	48.3	37.6	34.9	34.4
E (longitudinal), 10^6 psi	28.7	26.5	24.0	22.3
Compression				
CYS (longitudinal), ksi	173.1	147.9	139.5	117.6
E_c (longitudinal)	30.2	26.9	24.7	23.9
Shear(b)				
SUS (longitudinal), ksi	117.3	U(c)	U	U
Impact(d)				
V-notch Charpy, ft. lb.				
(longitudinal)	22.2	U	U	U
(transverse)	21.7	U	U	U
Fracture Toughness				
K_{Ic} (longitudinal), ksi $\sqrt{in.}$	48.2(e)	U	U	U
Axial Fatigue (longitudinal)(f)				
Unnotched, R = 0.1				
10^3 cycles, ksi	170	139	118	U
10^6 cycles, ksi	121	109	99	U
10^7 cycles, ksi	103	90	74	U
Notched, K_t = 3.0, R = 0.1				
10^3 cycles, ksi	136	90	76	U
10^6 cycles, ksi	39	53	48	U
10^7 cycles, ksi	30	50	42	U

17-4 PH ESR Data (continued)

Properties	RT	Temperature, F 700	900	1100
Creep (longitudinal)				
0.2% plastic deformation, 100 hr, ksi	NA	140	39	12
0.2% plastic deformation, 1000 hr, ksi	NA	130	18	4
Stress-Rupture (longitudinal)				
Rupture, 100 hr, ksi	NA	(h)	85	30
Rupture, 1000 hr, ksi	NA	(h)	50	16
Stress Corrosion(g)				
80% TYS, 1000 hr maximum	no cracks			
Coefficient of Thermal Expansion				
6.5×10^{-6} in./in /F (68 to 900 F)				
Density				
0.283 lb/in.^{3}				

(a) Values are average of triplicate tests conducted at Battelle under the subject contract unless otherwise indicated. Fatigue, creep, and stress-rupture values are from curves generated using the results of a greater number of tests.

(b) Double-shear pin-type specimen; average of 4 tests.

(c) U, unavailable; NA, not applicable.

(d) Average of 5 tests.

(e) Three longitudinal slow-bend specimens were tested. Specimen size was 0.750-inch thick by 1.500 inches wide with a span of 6 inches.

(f) "R" represents the algebraic ratio of minimum stress to maximum stress in one cycle; that is, $R = S_{min}/S_{max}$. "K_t" represents the Neuber-Peterson theoretical stress concentration factor.

(g) Room-temperature three-point bend test. Alternate immersion in 3 1/2% NaCl.

(h) Not determinable from test results.

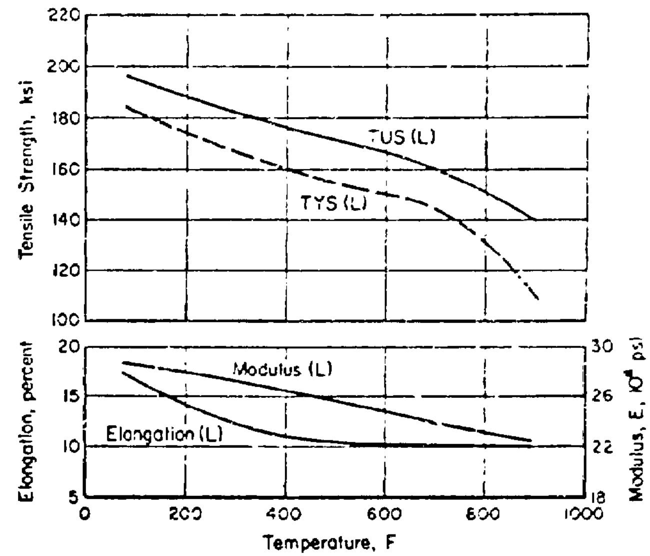

FIGURE 1. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF 17-4 PH (H900) BAR (ESR)

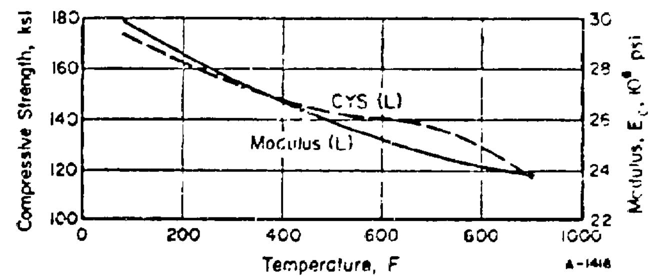

FIGURE 2. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF 17-4 PH (H900) BAR (ESR)

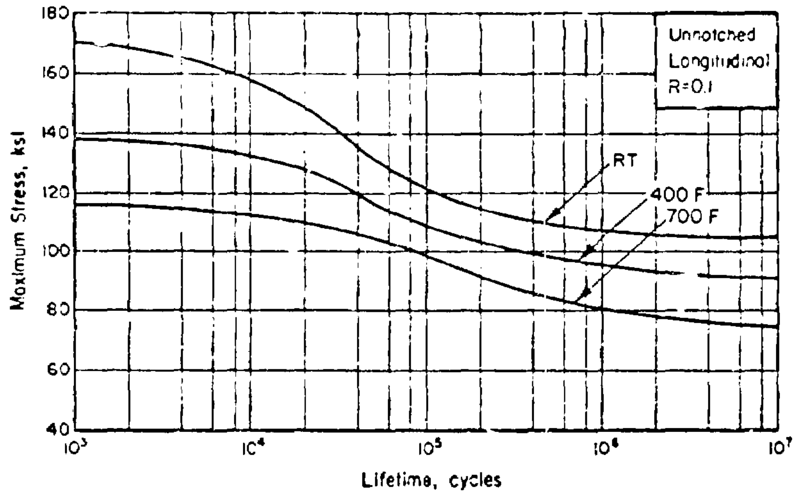

FIGURE 3. AXIAL LOAD FATIGUE RESULTS FOR UNNOTCHED 17-4 PH (H900) BAR (ESR)

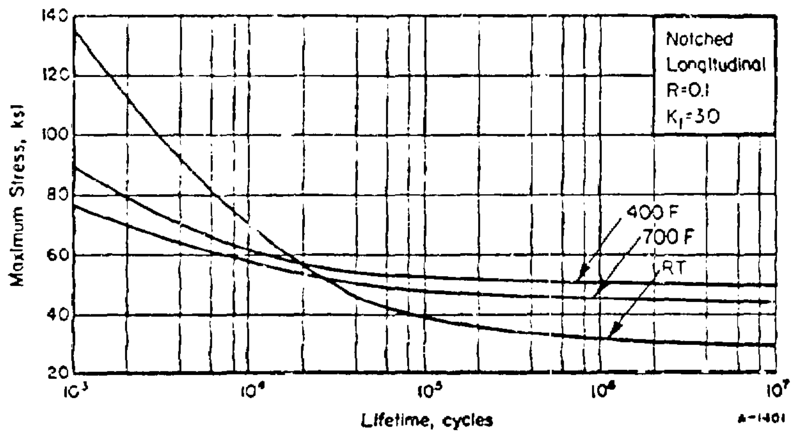

FIGURE 4. AXIAL LOAD FATIGUE RESULTS FOR NOTCHED (K_t=3.0) 17-4 PH (H900) BAR (ESR)

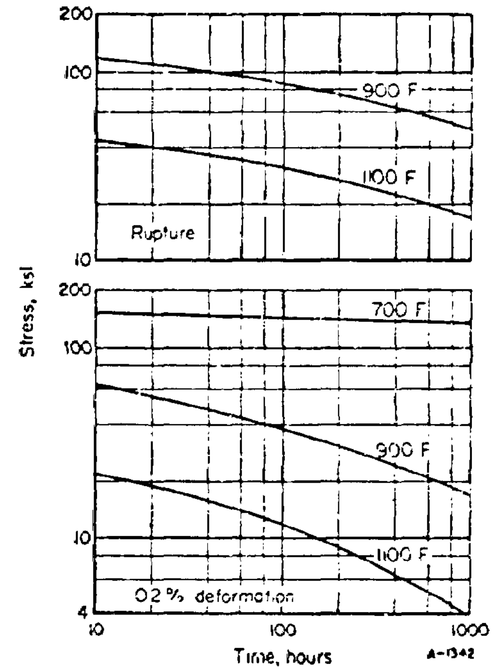

FIGURE 5. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR 17-4 PH (H900) BAR (ESR)

Udimet 710 Forged Bar

Material Description

Udimet 710 was recently developed by Special Metals Corporation to fill the need for a jet engine turbine blading alloy, combining the high strength and stability characteristics of Udimet 700 with the corrosion and sulfidation resistance of 18% chromium alloys such as the older Udimet 500 and Waspaloy. The alloy is designed for use in either the wrought or cast form. Data generated at Special Metals from laboratory heats show it to have rupture strengths superior to Udimet 700, good oxidation and hot corrosion resistance and excellent phase stability after extended exposure to stress and temperature. Data are now being generated from production scale heats for both cast and wrought forms.

The material used for this evaluation was Special Metal Corporation Heat No. 8-2814. The alloy was obtained as 1.875 inch diameter bar with the following composition:

Chemical Composition	Percent
Carbon	0.07
Manganese	0.10
Silicon	0.10
Chromium	18.0
Cobalt	14.8
Iron	0.14
Molybdenum	3.10
Tungsten	1.47
Titanium	4.88
Aluminum	2.51
Boron	0.018
Zirconium	0.04
Sulfur	0.003
Nickel	Balance

Processing and Heat Treating

Heat treatment, as suggested by Special Metals, was as follows:

(1) 2150 F for 4 hours, air cool,

(2) 1975 F for 4 hours, air cool,

(3) 1550 F for 24 hours, air cool,

(4) 1400 F for 16 hours, air cool.

UDIMET 710 Alloy Data(a)

Condition: Solution Treated and Aged
Product: 1.875-inch forged bar

Properties	Temperature, F RT	800	1200	1800
Tension				
TUS (longitudinal), ksi	177.7	166.1	183.9	55.0
TYS (longitudinal), ksi	138.0	122.8	122.9	37.0
e (longitudinal), percent in 2 in.	7.2	7.6	15.3	30.0
RA (longitudinal), percent	8.7	9.2	14.6	35.3
E (longitudinal), 10^6 psi	29.2	24.2	20.9	18.8
Compression				
CYS (longitudinal), ksi	149.7	127.0	118.5	37.3
E_c (longitudinal), 10^6 psi	30.6	25.5	22.5	18.2
Shear(b)				
SUS (longitudinal), ksi	126.3	U(c)	U	U
Impact(d)				
V-notch Charpy, ft. lb. (longitudinal)	27.8	U	U	U
Fracture Toughness				
K_{Ic} (longitudinal), ksi $\sqrt{in.}$	(e)	U	U	U
Axial Fatigue (transverse)(f)				
Unnotched, R = 0.1				
10^3 cycles, ksi	160	121	121	U
10^6 cycles, ksi	125	93	93	U
10^7 cycles, ksi	100	50	76	U
Notched, K_t = 3.0, R = 0.1				
10^3 cycles, ksi	139	83	74	U
10^6 cycles, ksi	66	47	44	U
10^7 cycles, ksi	27	27	40	U

UDIMET 710 Alloy Data (continued)

Properties	Temperature, F RT	1000	1400	1600
Creep (transverse)				
0.2% plastic deformation, 100 hr, ksi	NA	130	39	<1
0.2% plastic deformation, 1000 hr, ksi	NA	121	30	<1
Stress Rupture (long transverse)				
Rupture, 100 hr, ksi	NA	167	55	8
Rupture, 1000 hr, ksi	NA	160	12	2
Stress Corrosion[(g)]				
80% TYS, 1000 hr maximum	no cracks			
Coefficient of Thermal Expansion				
8.7×10^{-6} in./in./F (70 to 1400 F)				
Density				
0.292 lb/in.^{3}				

(a) Values are average of triplicate tests conducted at Battelle under the subject contract unless otherwise indicated. Fatigue, creep and stress-rupture values are from curves generated using the results of a greater number of tests.

(b) Double-shear pin-type specimen; average of 4 tests.

(c) U, unavailable; NA, not applicable.

(d) Average of 6 tests.

(e) Four longitudinal slow-bend specimens were tested. Specimen size was 0.750-inch thick by 1.500 inches wide with a span of 6 inches. The average K_Q obtained was 79.4 ksi$\sqrt{in.}$ Since the size ratio, 2.5 $(K_Q/TYS)^2$, was greater than both the specimen thickness and crack length in all tests, this K_Q value is not a valid K_{Ic} value by existing ASTM criteria.

(f) "R" represents the algebraic ratio of minimum stress to maximum stress in one cycle; that is, $R = S_{min}/S_{max}$. "K_t" represents the Neuber-Peterson theoretical stress concentration factor.

(g) Room-temperature three-point bend test. Alternate immersion in 3 1/2% NaCl.

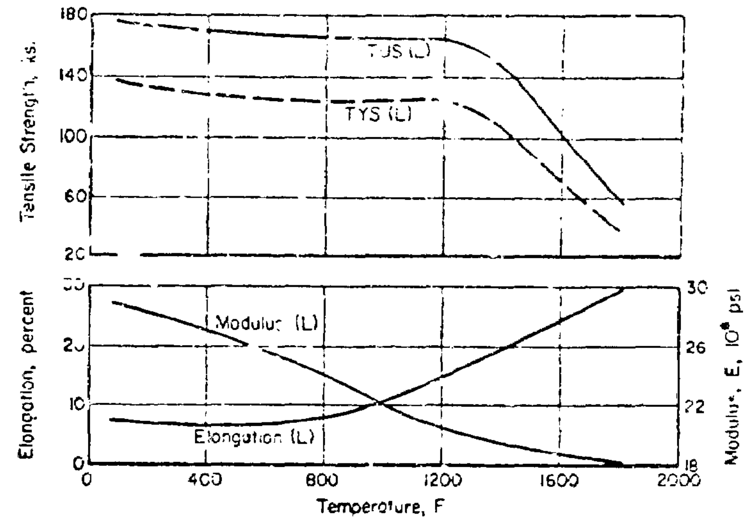

FIGURE 1. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF UDIMET 710 FORGED BAR

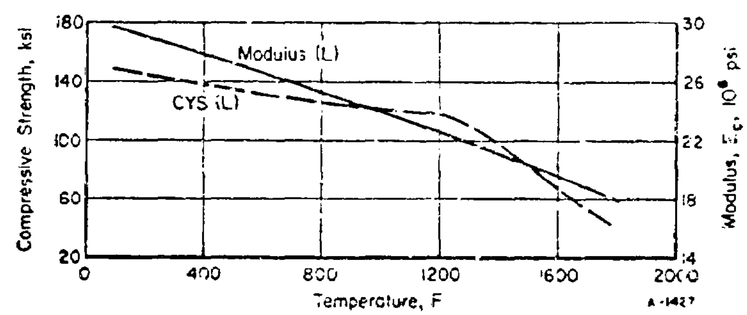

FIGURE 2. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF UDIMET 710 FORGED BAR

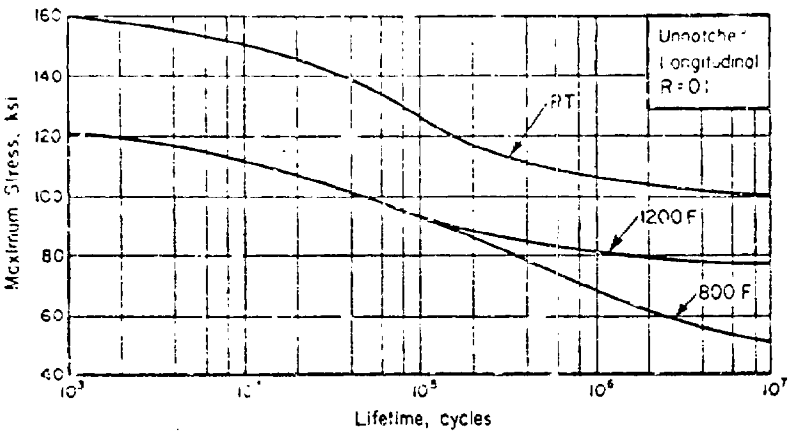

FIGURE 3. AXIAL LOAD FATIGUE RESULTS FOR UNNOTCHED UDIMET 710 FORGED BAR

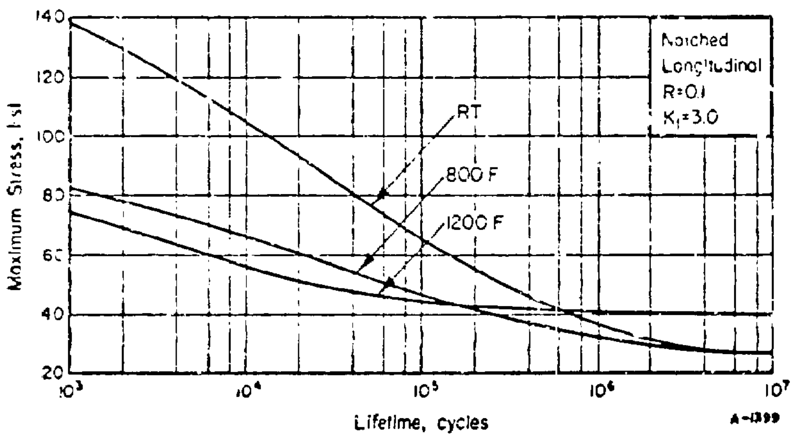

FIGURE 4. AXIAL LOAD FATIGUE RESULTS FOR NOTCHED (K_t= 3.0) UDIMET 710 FORGED BAR

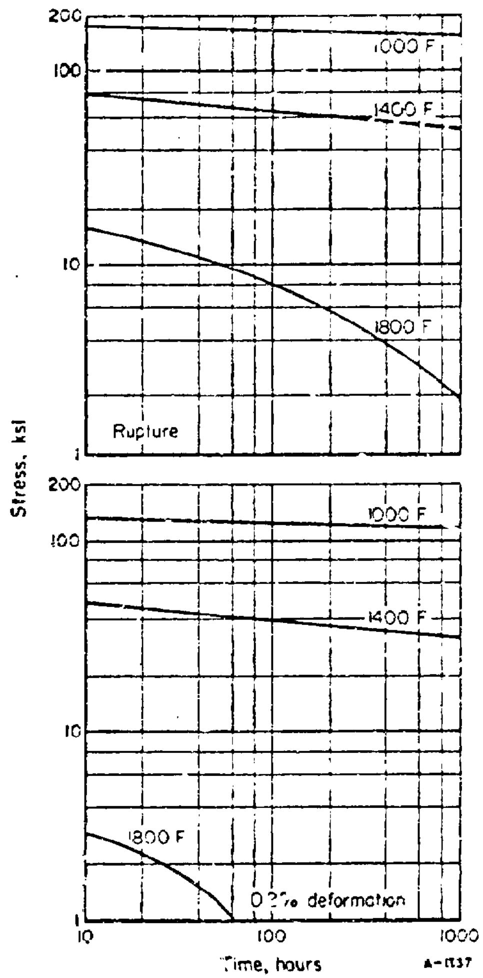

FIGURE 5. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR UDIMET 710 FORGED BAR

7050-T7E56 Hand Forging

Material Description

Alloy 7050 is an Al-Zn-Mg-Cu alloy developed by the Alcoa Research Laboratories supported by the Naval Air Systems Command and the Air Force Materials Laboratory. When heat treated and aged to the -T73 temper, thick 7050 plate and hand forgings exhibit strengths equal to or exceeding those of 7079-T6XX products combined with improved fracture toughness and a high resistance to exfoliation and stress-corrosion cracking. The alloy differs from conventional 7XXX series aluminum alloys in that zirconium is added and chromium and manganese are restricted in order to minimize quench sensitivity.

The material used for this evaluation was a 5-inch by 10-inch by 5-foot hand forging produced within the following composition limits:

Chemical Composition	Percent
Copper	2.0 to 2.8
Iron	0.15 max
Silicon	0.12 max
Manganese	0.10 max
Magnesium	1.9 to 2.6
Zinc	5.7 to 6.7
Chromium	0.04 max
Titanium	0.06 max
Aluminum	Balance

Processing and Heat Treating

The specimens were tested in the as-received -T7E56 temper.

7050-T7E56 Aluminum Alloy Data[a]

Thickness: 5-inch x 10-inch hand forging

Properties	Temperature, F			
	RT	250	350	500
Tension				
TUS (longitudinal), ksi	73.3	57.3	47.1	18.6
TUS (transverse), ksi	71.1	57.4	45.5	19.4
TUS (short transverse), ksi	72.1	U[c]	U	U
TYS (longitudinal), ksi	63.9	55.4	46.3	18.4
TYS (transverse), ksi	62.1	55.2	44.0	18.7
TYS (short transverse), ksi	58.9	U	U	U
e (longitudinal), percent in 2 in.	15.3	16.2	15.3	28.7
e (transverse), percent in 2 in.	5.7	15.8	16.0	25.2
e (short transverse), percent in 2 in.	6.3	U	U	U
RA (longitudinal), percent	39.2	47.9	61.9	82.5
RA (transverse), percent	7.8	35.5	46.7	80.8
RA (short transverse), percent	7.9	U	U	U
E (longitudinal), 10^6 psi	9.9	9.5	8.3	8.3
E (transverse), 10^6 psi	9.9	9.4	8.4	7.9
E (short transverse), 10^6 psi	9.8	U	U	U
Compression				
CYS (longitudinal), ksi	68.5	61.3	50.4	21.2
CYS (transverse), ksi	65.6	58.9	49.5	21.5
E_c (longitudinal), 10^6 psi	10.7	9.9	9.2	7.3
E_c (transverse), 10^6 psi	11.4	9.7	9.1	7.0
Shear[b]				
SUS (longitudinal), ksi	43.0	U	U	U
SUS (transverse), ksi	41.6	U	U	U
Impact[d]				
V-notch Charpy, ft. lb.				
(longitudinal)	11.3	U	U	U
(transverse)	2.1	U	U	U
Fracture Toughness				
K_{Ic} (longitudinal), ksi$\sqrt{in.}$	(e)	U	U	U
K_{Ic} (transverse), ksi$\sqrt{in.}$	28.8	U	U	U
Axial Fatigue (transverse)[f]				
Unnotched, R = 0.1				
10^3 cycles, ksi	53	49	42	U
10^6 cycles, ksi	42	30	24	U
10^7 cycles, ksi	30	22	18	U

7050-T7E56 Aluminum Alloy Data (continued)

Properties	RT	250	350	500
	Temperature, F			
Axial Fatigue (transverse) (continued)				
Notched, K_t = 3.0, R = 0.1				
10^3 cycles, ksi	50	50	43	U
10^5 cycles, ksi	21	21	17	U
10^7 cycles, ksi	12	12	12	U
Creep (transverse)				
0.2% plastic deformation, 100 hr, ksi	NA	40	16	3.5
0.2% plastic deformation, 1000 hr, ksi	NA	35	11	2.1
Stress Rupture (transverse)				
Rupture, 100 hr, ksi	NA	45	22	6
Rupture, 1000 hr, ksi	NA	38	14	4
Stress Corrosion(g)				
80% TYS, 1000 hr maximum	no cracks			
Coefficient of Thermal Expansion				
12.8×10^{-6} in./in./F (68 to 212 F)				
Density				
0.102 lb/in.^{3}				

(a) Values are average of triplicate tests conducted at Battelle under the subject contract unless otherwise indicated. Fatigue, creep, and stress-rupture values are from curves generated using the results of a greater number of tests.

(b) Double-shear pin-type specimen; average of 4 tests.

(c) U, unavailable; NA, not applicable.

(d) Average of 6 tests.

(e) Four longitudinal slow-bend specimens were tested. Specimen size was 0.750-inch thick by *1.500 inches wide with a span of 6 inches. The average* K_Q obtained was 62.6 ksi$\sqrt{in.}$ Since the size ratio, 2.5 $(K_Q/TYS)^2$, was greater than both the specimen thickness and crack length for longitudinal tests, this K_Q value is <u>not</u> a valid K_{Ic} value by existing ASTM criteria.

(f) "R" represents the algebraic ratio of minimum stress to maximum stress in one cycle; that is, $R = S_{min}/S_{max}$. "K_t" represents the Neuber-Peterson theoretical stress concentration factor.

(g) Room-temperature three-point bend test. Alternate immersion in 3 1/2% NaCl.

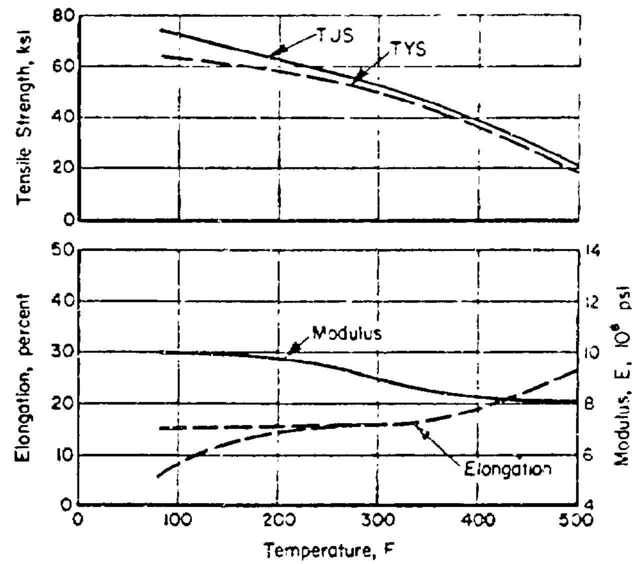

FIGURE 1. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF 7050-T7E56 HAND FORGING

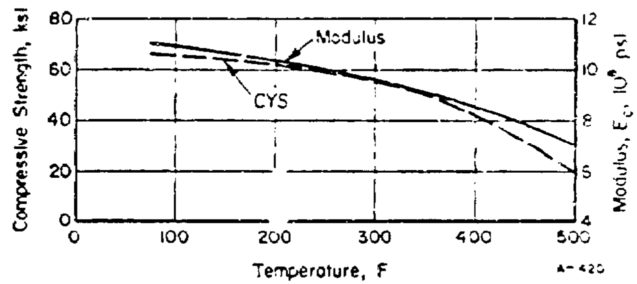

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FIGURE 2. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF 7050-T7E56 HAND FORGING

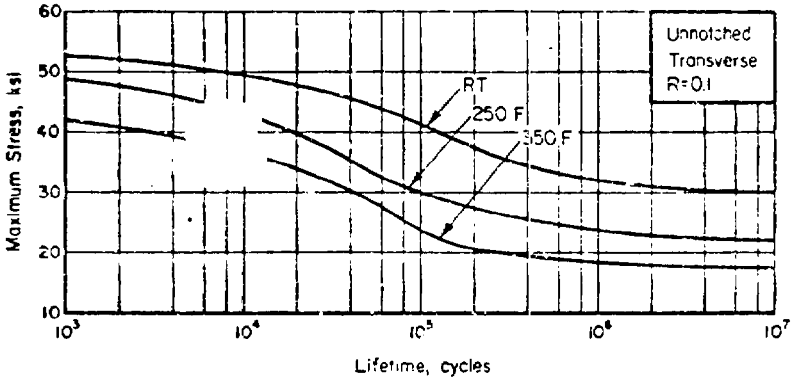

FIGURE 3. AXIAL LOAD FATIGUE RESULTS FOR UNNOTCHED 7050-T7E56 HAND FORGING

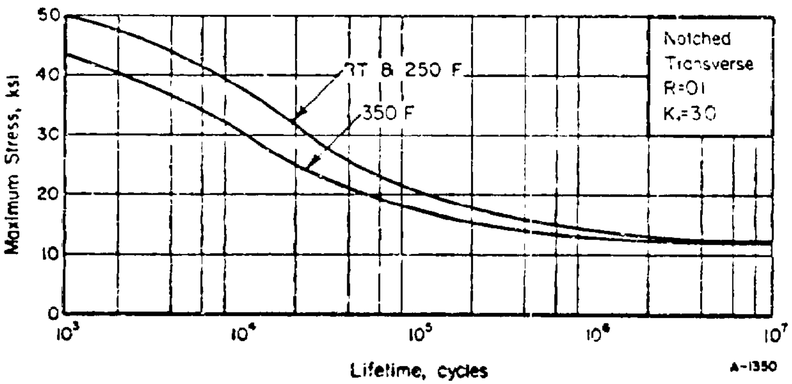

FIGURE 4. AXIAL LOAD FATIGUE RESULTS FOR NOTCHED (K_t = 3.0) 7050-T7E56 HAND FORGING

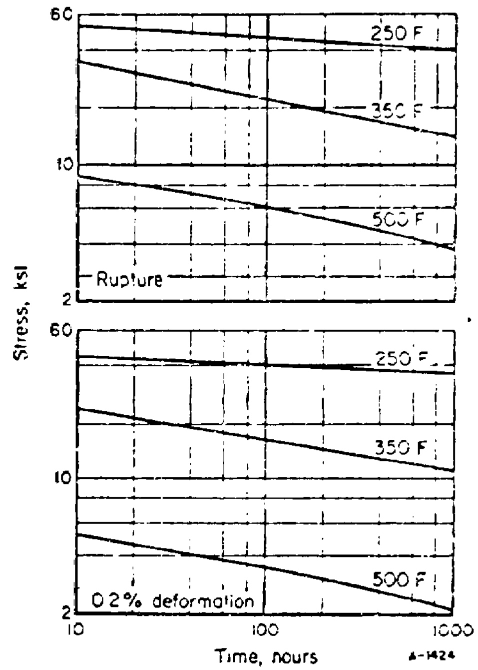

FIGURE 5. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR 7050-T7E56 HAND FORGING (TRANSVERSE)

2214-T351 Plate (Alcoa 417 Process)

Material Description

Alloy 2214 is a high-purity version of 2014 with closer controls on iron and silicon (Alcoa 417 process). The Alcoa 417 process, which utilizes only hot rolling and special controls during all stages of fabrication, is a more economic means for achieving the required properties without adversely influencing the overall engineering characteristics of the material. The material used in this evaluation was obtained from Alcoa as a 2 1/4-inch-thick plate within the following composition limits.

Chemical Composition	Percent
Silicon	0.50 to 1.2
Iron	0.3 max
Copper	3.9 to 5.0
Manganese	0.40 to 1.2
Magnesium	0.20 to 0.80
Chromium	0.10 max
Zinc	0.25 max
Titanium	0.15
Others	0.15 max
Aluminum	Balance

Processing and Heat Treating

Specimens were tested in the as-received -T351 temper.

2214-T351 Aluminum Alloy Data[a]

Thickness: 2 1/4-inch plate

Properties	Temperature, F RT	250	350	500
Tension				
TUS (longitudinal), ksi	64.9	56.1	51.7	26.1
TUS (transverse), ksi	66.0	57.2	53.2	26.8
TYS (longitudinal), ksi	46.8	41.8	37.6	19.7
TYS (transverse), ksi	42.7	38.4	35.9	18.4
e (longitudinal), percent in 2 in.	23.8	22.3	24.2	25.0
e (transverse), percent in 2 in.	21.0	23.8	21.0	21.5
RA (longitudinal), percent	34.2	39.7	60.9	71.5
RA (transverse), percent	27.6	33.5	41.9	64.3
E (longitudinal), 10^6 psi	10.5	9.9	9.4	8.0
E (transverse), 10^6 psi	10.5	9.8	9.1	7.9
Compression				
CYS (longitudinal), ksi	37.7	35.6	31.9	25.1
CYS (transverse), ksi	44.6	39.9	35.3	25.5
E_c (longitudinal), 10^6 psi	10.7	9.9	9.0	7.1
E_c (transverse), 10^6 psi	10.5	10.0	8.8	7.1
Shear[b]				
SUS (longitudinal), ksi	40.0	U[c]	U	U
SUS (transverse), ksi	36.9	U	U	U
Impact[d]				
V-notch Charpy, ft. lb.				
(longitudinal)	5.1	U	U	U
(transverse)	1.9	U	U	U
Fracture Toughness				
K_{Ic} (longitudinal), ksi$\sqrt{in.}$	(e)	U	U	U
K_{Ic} (transverse), ksi$\sqrt{in.}$	(e)	U	U	U
Axial Fatigue (transverse)[f]				
Unnotched, R = 0.1				
10^3 cycles, ksi	68	59	59	U
10^6 cycles, ksi	50	39	39	U
10^7 cycles, ksi	38	26	30	U
Notched, K_t = 3.0, R = 0.1				
10^3 cycles, ksi	47	43	43	U
10^6 cycles, ksi	24	21	21	U
10^7 cycles, ksi	14	11	14	U

2214-T351 Aluminum Alloy Data (continued)

Properties	RT	Temperature, F 250	350	500
Creep (transverse)				
0.2% plastic deformation, 100 hr, ksi	NA	37	13	2
0.2% plastic deformation, 1000 hr, ksi	NA	22	[illegible]	1
Stress Rupture (transverse)				
Rupture, 100 hr, ksi	NA	45	18	5
Rupture, 1000 hr, ksi	NA	39	13	3.5
Stress Corrosion[(g)]				
80% TYS, 1000 hr maximum	no cracks			
Coefficient of Thermal Expansion				
13.5 x 10^{-6} in./in./F (68 to 500 F)				
Density				
0.101 lb/in.^{3}				

(a) Values are average of triplicate tests conducted at Battelle under the subject contract unless otherwise indicated. Fatigue, creep, and stress-rupture values are from curves generated using the results of a greater number of tests

(b) Double-shear pin-type specimen; average of 4 tests.

(c) U, unavailable; NA, not applicable.

(d) Average of 4 tests.

(e) Six longitudinal and 6 transverse slow-bend specimens were tested. Specimen size was 0.750-inch thick by 1.500 inches wide with a span of 6 inches. Average K_c obtained was 45 ksi $\sqrt{in.}$ in the longitudinal direction and 50.8 ksi $\sqrt{in.}$ in the transverse direction. Since the size ratio, 2.5 $(K_c/TYS)^2$, was greater than both the specimen thickness and crack length in all tests, this K_c value is not a valid K_{Ic} value by existing ASTM criteria.

(f) "R" represents the algebraic ratio of minimum stress to maximum stress in one cycle; that is, $R = S_{min}/S_{max}$. "K_t" represents the Neuber-Peterson theoretical stress concentration factor.

(g) Room-temperature three-point bend test. Alternate immersion in 3-1/2% NaCl.

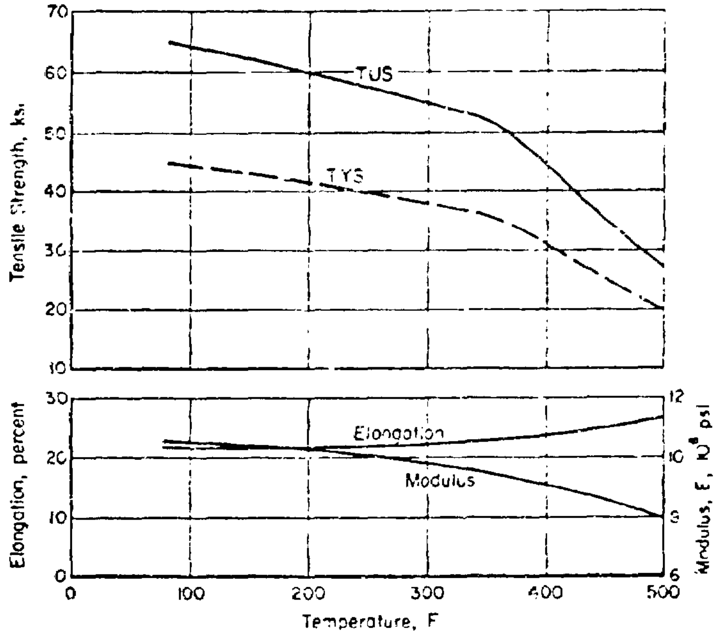

FIGURE 1. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF 2214-T351 PLATE

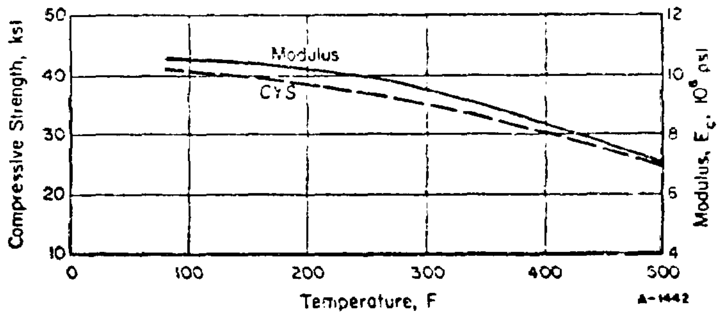

FIGURE 2. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF 2214-T351 PLATE

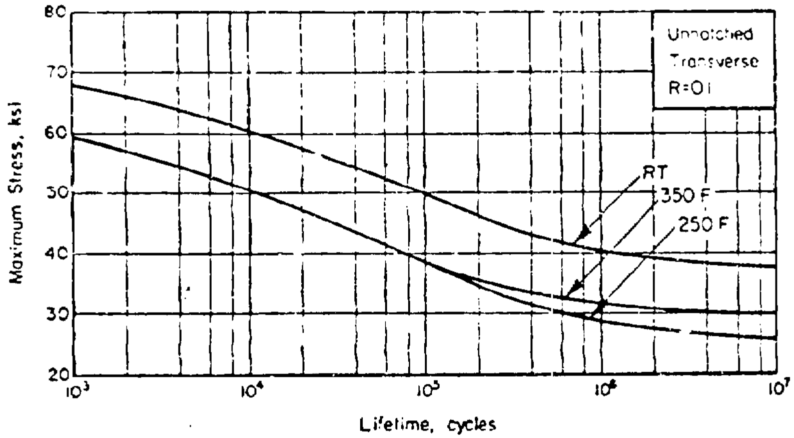

FIGURE 3. AXIAL LOAD FATIGUE RESULTS FOR UNNOTCHED 2214-T351 PLATE

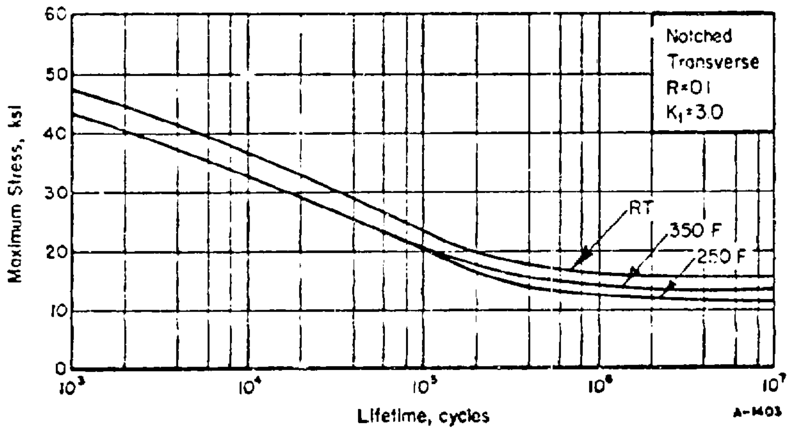

FIGURE 4. AXIAL LOAD FATIGUE RESULTS FOR NOTCHED (K_t = 3.0) 2214-T351 PLATE

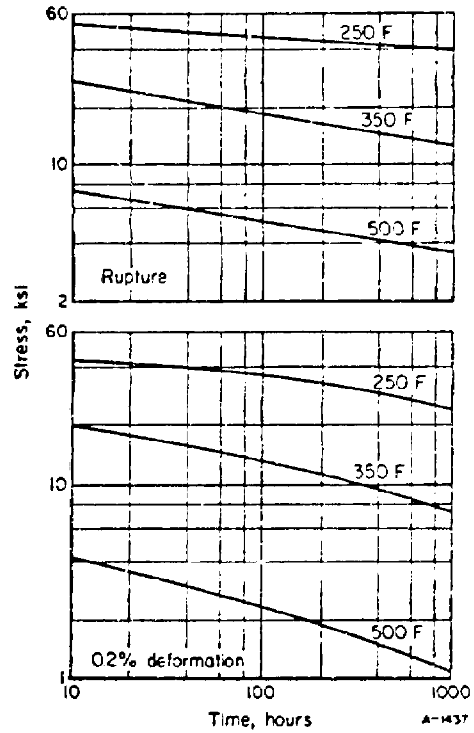

FIGURE 5. STRESS-RUPTURE AND ELASTIC DEFORMATION CURVES FOR 2214-T351 PLATE (TRANSVERSE)

Ti-6Al-4V Diffusion Bonded Component (DBHT)

Material Description

The material for this evaluation was supplied by the Air Force Materials Laboratory and consisted of pieces sectioned from a helicopter rotor hub. The rotor hub had been formed by diffusion bonding of 1/2-inch-thick Ti-6Al-4V plate. The evaluation material consisted of sections of the hub and lug ends. The material was tested in the as-received (diffusion bonded heat treated)(DBHT) condition.

Ti-6Al-4V Data(a)

Condition: Diffusion bonding heat treatment
Product: Diffusion bonded component

Properties	Temperature, F				
	RT	400	500	700	900
Tension					
TUS (transverse), ksi	151.3	123.3	U	107.0	94.4
TYS (transverse), ksi	143.3	139.3	U	88.7	80.9
e (transverse), percent in 2 in.	11.2	11.8	U	9.8	17.0
E (transverse), 10^6 psi	15.9	14.5	U	12.5	11.0
Compression					
CYS (transverse), ksi	146.3	111.3	U	97.1	92.8
E_c (transverse), 10^6 psi	17.9	16.6	U	15.3	14.5
Shear(b)					
SUS (longitudinal), ksi	92.5	U(c)	U	U	U
SUS (transverse), ksi	92.8	U	U	U	U
Impact(d)					
V-notch Charpy, ft. lb.					
(longitudinal)	14.2	U	U	U	U
(transverse)	13.2	U	U	U	U
Fracture Toughness					
K_{Ic} (longitudinal), ksi$\sqrt{in.}$	(e)	U	U	U	U
K_{Ic} (transverse), ksi$\sqrt{in.}$	(e)	U	U	U	U
Axial Fatigue (transverse)(f)					
Unnotched, R = 0.1					
10^3 cycles, ksi	125	125	U	98	U
10^6 cycles, ksi	87	87	U	77	U
10^7 cycles, ksi	60	60	U	56	U
Notched, K_t = 3.0, R = 0.1					
10^3 cycles, ksi	102	95	U	95	U
10^6 cycles, ksi	54	47	U	47	U
10^7 cycles, ksi	40	30	U	30	U

Ti-6Al-4V Data (continued)

Properties	RT	400	500	700	900
	Temperature, F				
Creep (transverse)					
0.2% plastic deformation, 100 hr, ksi	NA	U	101	65	11
0.2% plastic deformation, 1000 hr, ksi	NA	U	100	50	6
Stress Rupture (transverse)					
Rupture, 100 hr, ksi	NA	U	111	102	56
Rupture, 1000 hr, ksi	NA	U	110	100	35
Stress Corrosion(g)					
80% TYS, 1000 hr maximum	no cracks				
Coefficient of Thermal Expansion					
5.7 x 10^{-6} in./in./F (68 to 900 F)					
Density					
0.160 lb./in.^{3}					

(a) Values are average of triplicate tests conducted at Battelle under the subject contract unless otherwise indicated. Fatigue, creep, and stress-rupture values are from curves generated using the results of a greater number of tests.

(b) Double-shear pin-type specimen.

(c) U, unavailable; NA, not applicable.

(d) Average of 4 tests.

(e) Quantity of material insufficient for fracture toughness tests.

(f) "R" represents the algebraic ratio of minimum stress to maximum stress in one cycle; that is, $R = S_{min}/S_{max}$. "K_t" represents the Neuber-Peterson theoretical stress concentration factor.

(g) Room-temperature three-point bend test. Alternate immersion in 3-1/2% NaCl.

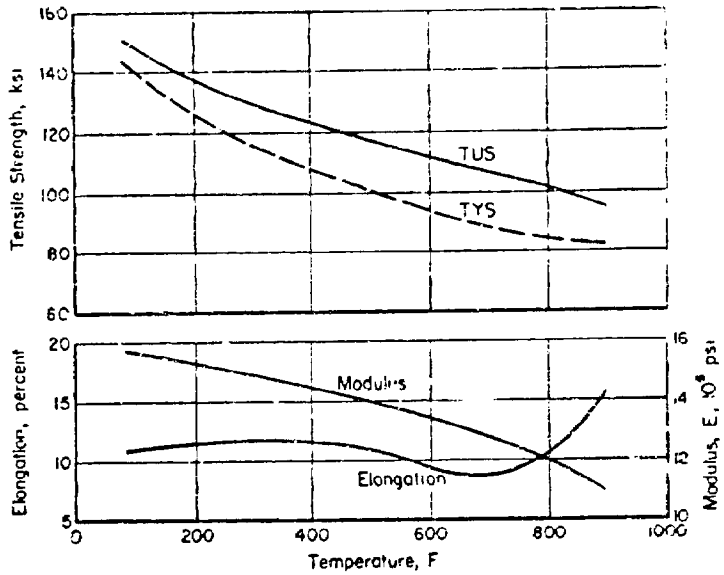

FIGURE 1. EFFECT OF TEMPERATURE ON THE TENSILE PROPERTIES OF Ti-6Al-4V DBC (DBHT)

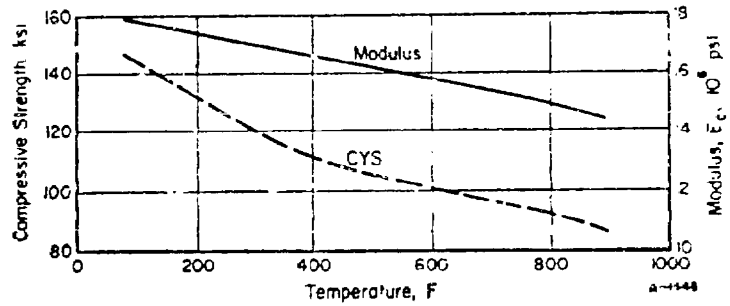

FIGURE 2. EFFECT OF TEMPERATURE ON THE COMPRESSIVE PROPERTIES OF Ti-6Al-4V DBC (DBHT)

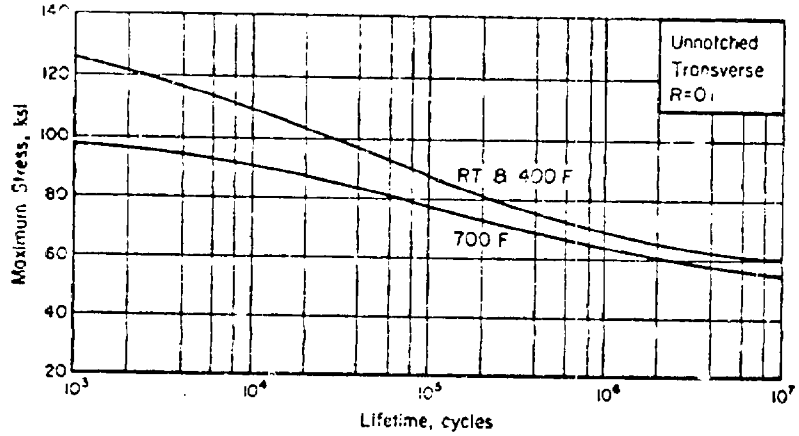

FIGURE 3. AXIAL LOAD FATIGUE RESULTS FOR UNNOTCHED Ti-6Al-4V DBC (DBHT)

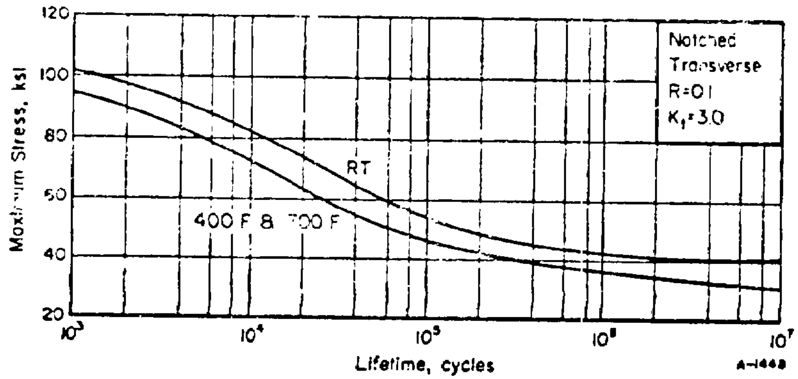

FIGURE 4. AXIAL LOAD FATIGUE RESULTS FOR NOTCHED (K_t = 3.0) Ti-6Al-4V DBC (DBHT)

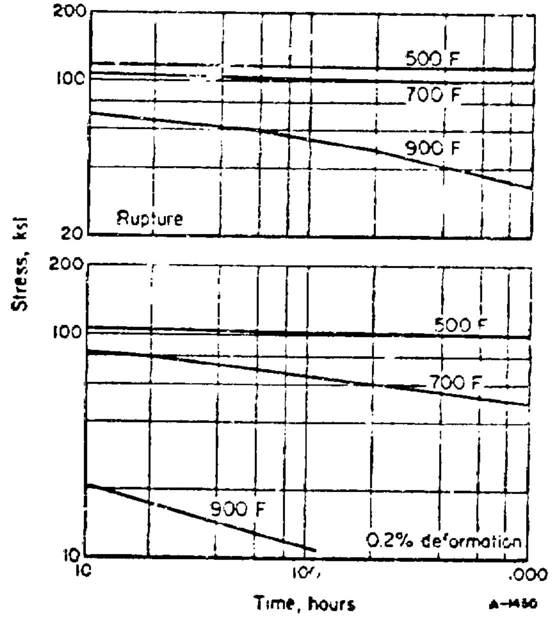

FIGURE 5. STRESS-RUPTURE AND PLASTIC DEFORMATION CURVES FOR Ti-6Al-4V DBC (DBHT)